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Regional Sediment Management (RSM) Program

Historical Sediment Budget (1860s to Present) for the United States Shoreline of Lake Erie

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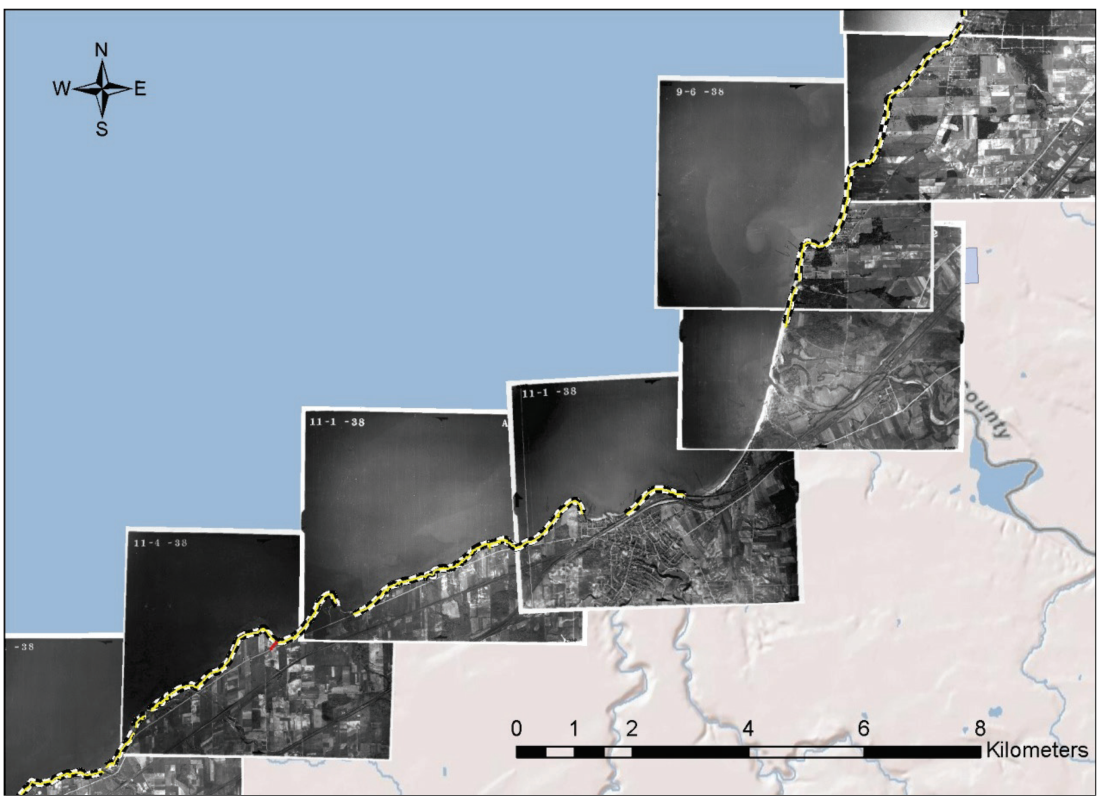
August 2016



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Final report

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Abstract

A sediment budget was developed for the U.S. shoreline of Lake Erie from Maumee Bay, OH, to Buffalo, NY, covering four time frames: (a) Pre-Armoring of the shoreline (1860s–1930s), (b) Mid-Century (mid-twentieth century, 1930s–1970s), (c) Recent era (1970s–2000s), and (d) Future expected conditions (2010+). Sources of data included historic U.S. Army Corps of Engineers Lake Survey charts, aerial photographs, and lidar survey data. The Ohio Department of Natural Resources provided historical recession lines for Ohio. The Pennsylvania Department of Conservation, Natural Resources, and the U.S. Geological Survey supplied historical bluff lines for Pennsylvania.

Analysis of harbor sedimentation and sediment bypassing provides verification of the volume of sediment calculated from bluff recession measurements. These volumes were consistent with harbor sedimentation or sediment bypassing measurements at most points along the shoreline, with the exception of underpredicting sediment volumes at Fairport Harbor, OH.

Most reaches show a decrease in bluff-supplied sediment over time. The decrease is a result of greater bluff armoring during the twentieth century, particularly after the 1970s. For New York and eastern Pennsylvania, the future projected sediment supply from bluffs is similar or slightly less than from the recent era. But in Ohio, the future supply is projected to decrease in most areas because of the almost complete armoring of the Ohio shore.

For the predicted future conditions, total eroded bluff volume will range from 15,000 cubic meters per year in Erie County, NY, to 200,000 cubic meters per year in Ashtabula County, OH.

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Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, D.C. under the USACE Regional Sediment Management (RSM) Program; Project 454632, “Lake Erie Regional Sediment Management Study” Project. The HQUSACE RSM Program Manager was Linda S. Lillycrop, CEERD-HN-C. Jeffrey A. McKee was the HQUSACE Navigation Business Line Manager overseeing the RSM Program.

The work was performed by the U.S. Army Engineer District, Buffalo (LRB) and by the Coastal Engineering Branch (CEERD-HN-C) of the Navigation Division (CEERD-HN), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Tanya M. Beck was Chief, CEERD-HN-C; Jackie S. Pettway was Chief, CEERD-HN; and W. Jeff Lillycrop (CEERD-CHL) was the ERDC Technical Director for Civil Works and Navigation Research, Development, and Technology Transfer (RD&T) portfolio. The Director of ERDC-CHL was José E. Sánchez.

The Commander of ERDC was COL Bryan S. Green, and the Director was Dr. Jeffery P. Holland.

Unit Conversion Factors

Multiply	By	To Obtain
cubic meters	1.308	cubic yards
cubic yards	0.765	cubic meters
feet	0.3048	meters
meters	3.281	feet
meters	5.396×10^{-4}	miles (nautical)
meters	6.214×10^{-4}	miles (U.S. statute)
miles (nautical)	1852	meters
miles (U.S. statute)	1609.34	meters
square meters	3.861×10^{-7}	square miles
square miles	2.59×10^{6}	square meters

Metric units are used in this report except for historical dredging volumes, which are shown in cubic yards, as per common use in dredging records and contractual documents in the United States. Dredging volumes, even when converted to metric, have been reported in the same number of significant digits shown in the original source data. Volumes in the computed sediment budget have been rounded to the nearest 100 cubic meters (m^3).

1 Introduction

Background

The U.S. Army Corps of Engineers (USACE) District, Buffalo (hereafter, the Buffalo District), has recently been implementing principles of Regional Sediment Management (RSM) into projects and studies along the southern Lake Erie shoreline. Historically, sediment studies were isolated to individual projects along a limited stretch of shoreline. It is now recognized that sediment management must be addressed on a regional basis because engineering activities or construction that influences sediment processes in one location can have unforeseen consequences tens or hundreds of kilometers (km) away. Managing sediment to benefit a region will reduce costs, allow use of natural processes to solve engineering problems, and improve recreation resources and natural habitat.

Geology and sediment sources[1]

General

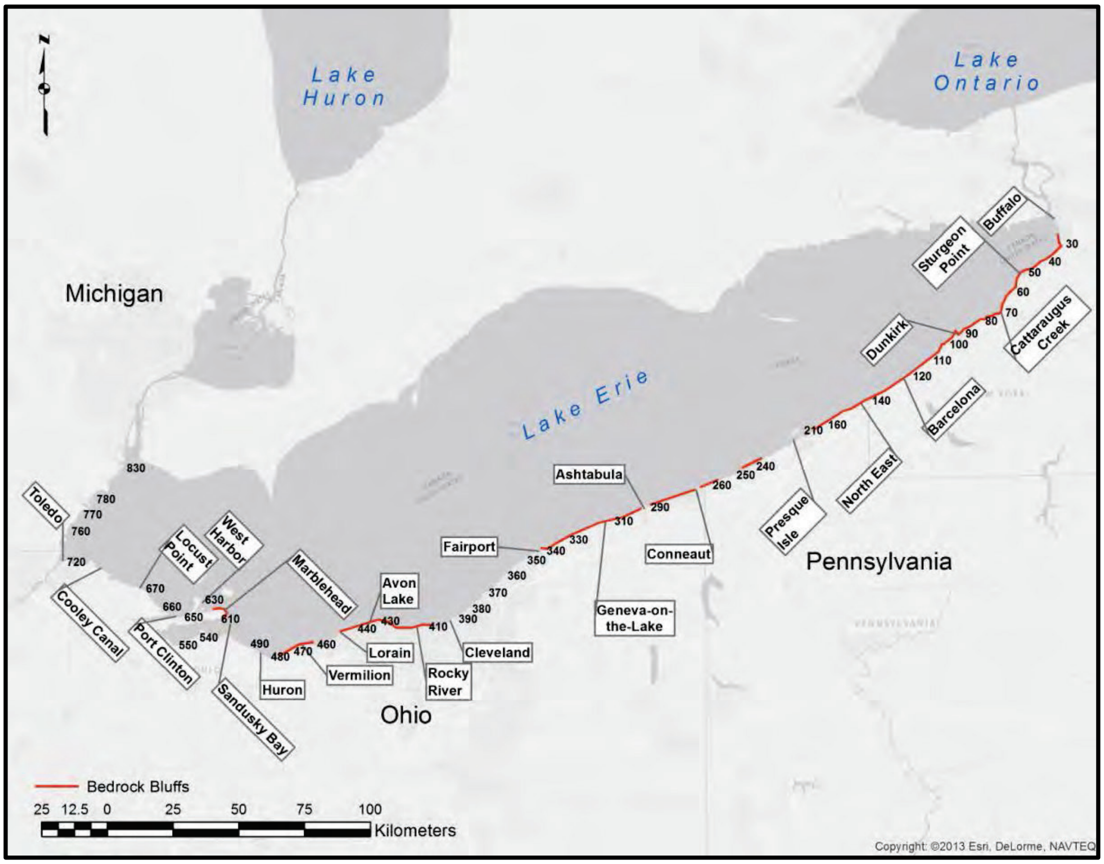
The study area covers the U.S. shoreline of Lake Erie between Maumee Bay, OH, and Buffalo, NY. From Toledo in Lucas County, OH, the shore continues southeast past Sandusky Bay to Huron, OH. East of Huron, the shoreline orientation turns to northeast and continues through Ohio, Pennsylvania, and New York to the city of Buffalo in Erie County, NY, at the northeast end of the lake (Figure 1).

In low-relief areas of western Lake Erie, modern sediments of variable thickness overlie Pleistocene glacial drift (Fuller 1996; Ohio Department of Natural Resources 2007). Beaches are composed of sand, gravel, and shell hash. Some of the beaches are mainland attached whereas others are barriers that enclose marshes. Rock fragments from upland sources are delivered via streams and from erosion of onshore and nearshore deposits. The shell content of beaches increased after the 1987 invasion of the zebra mussel and the more recent invasion of the quagga mussel. In some places, shells compose almost 100% of the beach sediment. Organic material is also often found on beaches. This is exhumed from wetland deposits that are exposed on the lakebed as barrier beaches recede. Dredging of the

[1] Adapted from Morang and Melton (2001) and Morang et al. (2011).

major tributaries during the last century has significantly reduced the volume of sand and gravel provided from upland sources (Guy and Rockaway 2004). Jetty construction, bluff and shore armoring, and other factors discussed later also contributed to reduced sand supply. Sand spits like the Cedar Point Peninsula were once fed by a generous supply of littoral material, but most of these features are now vulnerable to wash-over and inundation and as a result, have been largely armored (Morang and Chader 2005).

Figure 1. Lake Erie study area. Solid line shows shale and limestone bedrock exposures along the lakeshore, in some areas, at the water line. Adapted from Holcombe et al. (2005). Numbers represent 1 km reaches used in this present study.



Most of the Pennsylvania and New York shore of Lake Erie consists of bluffs, usually less than 10 meters (m) high, composed of soft glacial deposits (primarily unconsolidated glacial till and glacio-lacustrine sediments) that overlie shale and siltstone bedrock (Figure 1 and Appendix A) (Geier and Calkin 1983). The elevation of the bedrock/till interface is a predominant factor in shaping and molding the morphology along this part of the lakeshore. Typically, where the interface is above the water level, the lake shoreline reaches to near-vertical bluffs that are devoid of beaches.

Occasional failures occur when large blocks of the bluffs collapse, but for the most part, these exposed bedrock sections resist erosion much more than till bluffs.

In contrast, where the bedrock interface is at or below the water level, the bluffs are composed of much more vulnerable unconsolidated glacial till at the base of which a sand/gravel beach may be present. These beaches are formed from both locally derived sediment and material moved alongshore as littoral drift. The fact that littoral sediment moves from west to east along the Pennsylvania shore over great distances was verified during a coastal processes study conducted at North East Marina, PA, in 2001 (Morang and Melton 2001). At the site, irregularly shaped rubber blocks with characteristic protrusions were lying in the surf zone and on the beach. The rubber came from a landfill at Erie that collapsed, dumping debris into the lake. Within a few years, the rubber blocks had moved east over 30 km.

Geier and Calkin (1983) concluded that the most important single control of erosion rates along unprotected stretches of the New York shore was the composition of the material in the bluffs and the height of the bedrock.

Areas where the bedrock extended 4 m or more above lake level had statistically lower erosion rates than the areas where till bluffs were accessible to storm waves.

Bedrock

In coastal Ohio, the bedrock consists of the Ohio Shale and is above lake level near Avon Lake, in Bay Village, and Lakewood (Stone et al.[1]). East of Cleveland the glacially-eroded rock surface is approximately at present lake level and is overlain by the Ashtabula Till.

Along the Pennsylvania shore, exposed bedrock is part of the Devonian Age Canadaway Formation, locally known as the Northeast Shale (Taylor and Buyce 1994). The bluffs contain poorly differentiated sequences of inter-bedded shales, claystones, siltstones, and sandstones (Knuth 2001). Near the town of North East, the bedrock layers dip approximately 5° to

[1] Stone, B. D., R. R. Pavey, J. A. Fuller, and D. S. Foster. Unpublished report. Map of surficial surface materials in the Lake Erie coastal area, northeastern Ohio. U.S. Geological Survey Open-File Report. Denver, CO: U.S. Geological Survey Publications Warehouse.

the southwest and are fractured by irregular joints. Because of the joints, offshore exposures resemble a series of flat terraces with irregular edges. Similar terraces occur near Dunkirk, NY, and farther east (Figure 2).

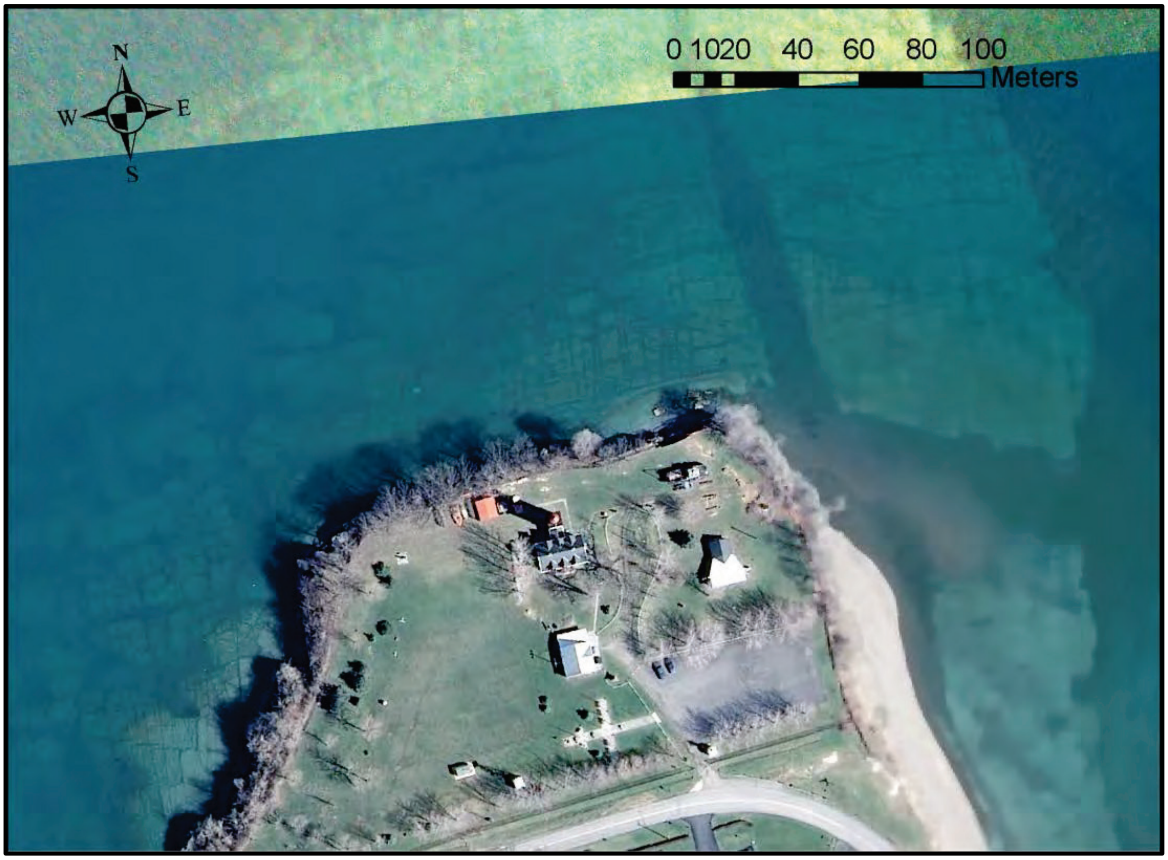
Bedrock on the beach and in the shallow near-shore can be a source of cobbles and coarse gravel beach sediment. During storms or during ice movement, pieces of shale break off from the edges of the terraces. Joints within the flat units are enlarged over time as they fill with cobbles and boulders that serve as abrasive agents. Aprons of debris eroded from the jagged edges of the terraces are seen at the base of many of the steps. Some of these loose pieces move onto the beach, becoming part of the coarse cobble. Over time, the angular blocks are broken down into smaller and smaller pieces, eventually becoming sand sized. Examination of beach sand near North East Marina using a hand-held magnifier revealed that the sediment has been sorted alongshore. The brown fine-grain sand on the beach west of the marina's west wall was mostly well-rounded quartz with various dark minerals, but the sand at the mouth of Twentymile Creek approximately 1 km east of the marina was grey and much coarser, consisting of approximately 50% shale fragments (Morang and Melton 2001).

Knuth (2001) also documented this process of sediment being supplied from offshore terraces:

> Since bedrock is exposed at or near mean water level for both the western and eastern reaches, erosion of the exposed layers by plucking and abrasion adds to the sedimentary load. Large shingles and flagstones make up a substantial portion of some beaches devoid of fine- to coarse-grained sands. As the shingles are reduced in size by milling, the silt and clay fractions are released and dispersed offshore. The smaller shingles are carried by the longshore transport system and make up a portion of the beaches downdrift.

A fundamental question is how long does shale remain on the beach as sand-size or greater fragments? Field tests with blocks of measured and marked shale or shale slakability tests in a geotechnical laboratory will be needed to provide answers.

Figure 2. Shale slabs offshore Dunkirk, NY. Jointing and patterns can be seen through the clear water. Photography 2008.



Till

Pleistocene glacial deposits overlie the Devonian shale and siltstone. These deposits include unconsolidated tills composed of cobble in a matrix of sand, silt, and clay overlain by lacustrine sands (Taylor and Buyce 1994). Often the lower portions of the till contain large stones from the local bedrock, up to 80% by volume (Geier and Calkin 1983). The upper till unit is sometimes thinly stratified and is characterized by stiff to very stiff cohesive clayey silt to silty clay, sometimes also containing traces of fine sand and gravel-shale fragments (Knuth 2001).

The till bluffs vary greatly in composition along the shore as well as within the stratigraphic section and are much more susceptible to wave erosion than the bedrock. Carter (1977) collected 10 till samples from along the Lake Erie shore between Silver Creek, NY, and Marblehead, OH. The coarse fraction of the till ranged from 8% to 40%. Carter (1977) settled on an average coarse fraction of 25%, concluding that this value may be high by approximately 5%.

Conneaut, OH, to Presque Isle, PA. Table 1 lists sand/gravel percentage summarized from various sources.

Table 1. Till composition, Conneaut, OH, to Presque Isle, PA.

Location	Source	Measured Percent Sand/ Gravel	Sand/Gravel Percent Used for Sediment Budget	Applied to Reaches
Ohio-Pennsylvania border	D'Appalonia[1]	24.8	25	262-263
Girard, PA	Table 4, Carter 1975	24		
PA recession control site 1	Table 5, Knuth 2001	27.5	27	259-261
PA recession control site 4	Table 5, Knuth 2001	6.8	7	254-258
PA recession control site 13	Table 5, Knuth 2001	19.3	19	248-253
PA recession control site 14	Table 5, Knuth 2001	23	23	226-246

[1]D'Appalonia Consulting Engineers, Inc. Unpublished report. Geotechnical investigations: Proposed Greenfield site. Pittsburgh, PA: United States Steel Corporation.

Erie to Buffalo. In 1985, the Buffalo District collected samples from the bluffs between Erie and North East, PA, and conducted geotechnical tests to determine the clastic (sand and gravel) content of the till bluffs. Values ranged from 11% to 74%. For samples collected by Geier and Calkin (1983) in New York, sand and gravel content ranged from 0% to 39%. An average of 25% was applied as the till factor through this reach.

Ohio and remainder of New York shoreline. Detailed sieve analysis is not available for the remainder of the shoreline within the study area.

For the purposes of this present study, a coarse fraction of 20% was assumed for areas lacking detailed till sampling data.

Given the high level of variability within the till units eroding into the lake, a detailed analysis measuring the coarse fraction at a higher resolution would provide a greater degree of certainty of the sediment values entering the lake.

Lacustrine layer

Some of the higher bluffs and a low area east of Van Buren Point, NY, are capped with a layer of lacustrine deposits. The unit consists of soft to very stiff finely interbedded clayey silt to silty clay with some silt partings and rare shale fragments (Knuth 2001). Because the soft material is so

vulnerable to waves, homeowners in Van Buren Bay built seawalls or gabions to protect their property. When exposed to waves, much of this material disperses into deeper water, forming sediment plumes (Figure 3).

Beach sand

Layers of beach sands up to 2 m thick overlie some of the higher bluffs in Pennsylvania. Sand blankets the shore-face off Cattaraugus Creek, NY, and near Evans Beach Park, NY, and narrow beaches follow the bluffs in restricted areas throughout the study area. For Pennsylvania beaches, Knuth (2001) reported that the sand/gravel proportion ranged from 90% to 99%. D'Appalonia[1] measured 96% at the Ohio-Pennsylvania border. This present study uses a value of 95% for the sediment budget calculations.

An unknown, and probably greatly variable, amount of sand may be lost offshore as a result of ice rafting. Barnes et al (1993) examined ice transport in Lake Michigan beaches in the early 1990s and concluded that in northern Illinois, quantities entrained may be similar to the amount of sediment supplied by bluff erosion. Conditions along Lake Erie's shore are different in that many bluff areas have bedrock exposure above the water line without a flanking beach. The bedrock will be more resistant to ice than sand beaches. Additionally, shallowness of the lake allows the ice to grow/melt more quickly, and the entire lake may become ice covered. The timing of ice formation and storms further complicate the potential for erosion and transport from the near-shore ice complex. In the sediment budget developed in this project, some cells required an offshore loss factor to balance. Ice rafting may be responsible for some of this offshore loss. This is a mechanism that needs a field study to quantify.

Cedar Point Peninsula

The shale/till bluffs end west of Huron, OH, near the Sawmill Creek Golf Course. From there the Cedar Point Peninsula extends west into the mouth of Sandusky Bay. This sand spit was formerly fed by littoral transport from the east. It was probably a stable or growing geomorphic feature before the mid-1800s when European settlement and industrialization caused profound disruptions to the coastal sediment regime. Construction and urbanization diminished sediment supply as a result of

[1] D'Appalonia Consulting Engineers, Inc. Unpublished report. Geotechnical investigations: Proposed Greenfield site. Pittsburgh, PA: United States Steel Corporation.

- armoring bluffs
- interrupting littoral sediment transport patterns by harbor jetty construction
- trapping sediment at harbor fillets
- depositing material dredged from river mouths into deep water or onto land.

Figure 3. Sediment plume rounding Van Buren Point, NY. The shore along the bay consists of till overlain by lacustrine deposits. Photography: 2004 Chautauqua County 24-inch (in.) Resolution Natural Color Orthoimagery from NYSGIS Clearinghouse.

Morang and Mohr (2007) and Morang et al. (2011) provide a more complete discussion of Lake Erie sediment losses and inputs. The Ohio Department of Natural Resources (ODNR), Office of Lake Survey, conducted many years of research on Ohio counties and lakefront geological processes (Benson 1978; Carter 1976; Carter and Guy 1980, 1983; Carter et al. 1986).

During the late-1800s, the only way to reach the Cedar Point amusement park was by steamboat. To increase business, a 10 km paved road known as Chausee opened in 1914. Originally a sand beach extended along the lake

side of the roadway. Because of steady erosion over the decades, much of the lake side of the roadway has been protected with a rock revetment, effectively fixing the position of the shoreline. The eastern portion of the roadbed along Sheldon Marsh Nature Preserve disappeared as a result of steady beach erosion during the twentieth century (Morang and Chader 2005).

Even if sediment were available, the Cedar Point peninsula is now fixed in position and could not grow to the west. The tip of the peninsula was first stabilized in 1844 when wood cribs were built to fill breaches that threatened the safety of the harbor (U.S. Army Corps of Engineers [USACE] 1941). In 1898, Congress authorized the jetties to be extended as far as necessary to maintain currents across the bar. A dike with several small spurs was built along the west side of the sand spit. The protective structures now consist of over 3 km of rubble-mound stone breakwaters, dikes, and jetties (USACE 2010).

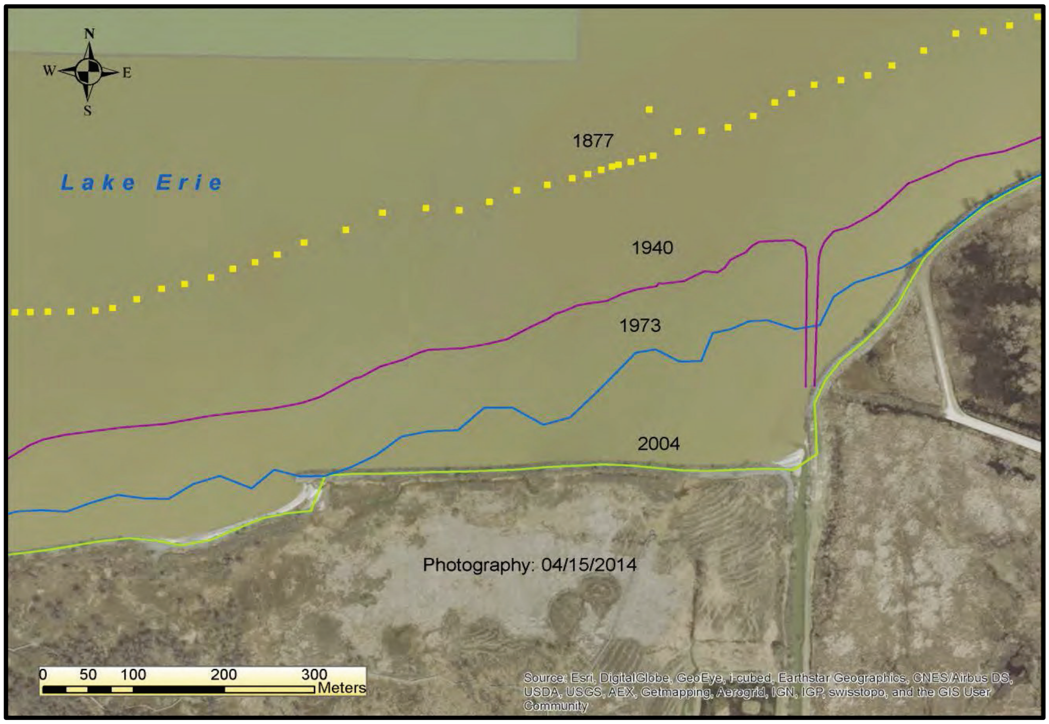
Marshy/lacustrine sediments, West Lake Erie

West of Catawba Island, the Ohio shore becomes low and marshy with occasional sand spits and limited beaches. Most of the terrain consists of Late Wisconsinan lake-wave deposits (ODNR 2007). In northwest Ohio, the relatively soft bedrock was repeatedly scoured by glacial ice flowing southwest from the Erie Basin, which destroyed most of the pre-existing drainage systems and allowed for deposition of thick layers of drift. The upper surface was smoothed away by wave action in the pro-glacial lakes that formed at the margin of the retreating Wisconsinan glaciers (the most recent major advance of the North American ice sheet complex). Thickness of the glacial drift ranges from 15 to 18 m, with less accumulation in Maumee Bay. The underlying bedrock consists of Ordovician fractured shale and Trenton limestone, from which oil is produced in the Toledo Field (ODNR 2007).

Because of the soft and highly erodible glacial drift and lacustrine deposits, the shoreline has suffered severe recession during the twentieth century.

Net littoral transport is to the west. As a response to the erosion, many kilometers of coastline have been armored with dikes and rock revetment (Figure 4).

Figure 4. Shoreline recession in Maumee Bay, OH. Much of the shore is now protected with a levee and rock revetment. Shoreline data from ODNR; photography 15 April 2014 from Esri.



Objective

There are three objectives of this study. First, this sediment budget and analysis of bluff line change and harbor sedimentation are expected to determine sediment movement along the lakeshore and improve planning of shoreline management. Second, the study will lead to better decision making for planning for maintenance dredging and harbor structure projects to reduce sedimentation in Federal channels. Third, the Buffalo District RSM program plans to use this study to provide information to initiate beneficial use of dredged material for ecosystem restoration projects along the Lake Erie shore.

In addition to the main objectives, an important element in implementing RSM along the Lake Erie shore is to develop a sediment budget for the purposes of

- gaining a better understanding of coastal processes in the area
- identifying effects of harbor structures on these processes
- identifying sources and pathways of sediment
- determining if sediment sources have changed over a century due to engineering activities and bluff armoring.

Approach

This report describes the development of a sediment budget for the Lake Erie coast between Maumee Bay, OH, and Buffalo, NY (Figure 1), prepared by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), and the Buffalo District. The sediment budget covered four time frames representing different stages in development along the lakeshore:

- Pre-Armoring of the shoreline (1860s–1930s)
- Mid-Century (mid-twentieth century, 1930s–1970s)
- Recent era (1970s–2000s)
- Future expected conditions (2010+).

Note that although development and shoreline armoring were occurring in the Pre-Armoring time frame, the majority of the lakeshore was in a natural state and is therefore treated as a baseline condition.

The study area did not include

- armored (artificial) lakefront at Buffalo, Erie, Cleveland, and Sandusky
- low shores within Sandusky Bay
- the Ohio islands
- sediment contributions between the Detroit River and Maumee Bay
- sediment contributions or transport west of Toledo.

The general approach to develop the sediment budget and conduct the analyses is described in the subsequent chapters of this report. In order to develop the sediment budget, shoreline and bluff line data were collected from a number of sources (Chapter 2). Data were organized and displayed in Esri ArcMap GIS software. Bluff lines and shorelines were traced in ArcGIS (Chapter 3). The Digital Shoreline Analysis System (DSAS) was used to calculate bluff line and shoreline change rates (Chapter 4). To determine the magnitude of sediment accumulation at each Federal harbor, bathymetric data were analyzed (Chapter 5). The sediment derived from bluffs and beaches was measured and used as input for the sediment budget (Chapter 8). Finally, the sediment budgets (pre-armoring, mid-century, recent era, and future expected conditions) were calculated based on the data and analyses (Chapter 8-11).

2 Data Sources

Existing shoreline/bluff line data

Ohio

The ODNR supplied shoreline/bluff line files generated by the Office of Lake Survey. These included an 1870s line (with earlier and later dates in some areas), along with 1973, 1990, and 2004 lines. The 1990 file was not needed for this present study, and the 2004 file was used as the contemporary condition (versus 2008–2009 in New York). Because a 1930s shoreline was not available for the Ohio shore, a 1937–1938 bluff line was drawn from historical aerial photography (described subsequently).

Pennsylvania

Pennsylvania Sea Grant supplied a 1991 bluff line and shoreline covering the entire Pennsylvania Lake Erie shore, and the U.S. Geological Survey (USGS) supplied 1938, 1998, and 2006 bluff lines (Hapke et al. 2009).

New York

Only limited historical bluff line data are available in digital vector form for New York. The National Oceanic and Atmospheric Administration's (NOAA) Shoreline Data Explorer lists a 2006–2007 shoreline. Based on comparisons with 2008 aerial photography, the 2006–2007 shoreline represents the water-land interface only and does not follow the bluff edge in bluff areas. Therefore, these data were not suitable for this study. No other digital shorelines or bluff lines were identified from any other source.

Historical USACE coastal charts are available from NOAA, Office of Coast Survey, Historical Map, and Chart Project. These files are raster images and must be geo-referenced for use with Geographic Information System (GIS) software. The geo-referencing process is described later in the report.

Aerial photography--contemporary

Ohio

Initially, this project used 2007 imagery from the Ohio Statewide Imagery Program (OSIP). Mosaics for entire counties can be downloaded as single files but the files are large and cover more land area than was needed in this project.

Midway through the project, it proved more efficient to use imagery accessed online from Esri Maps and Data. This Esri imagery consists of satellite data supplied by various commercial and government organizations and covers the entire United States. Ohio coverage was dated September 2009 and was full color with 0.3 m pixel resolution.

Pennsylvania

The Pennsylvania Spatial Data Access (PASDA) is the Commonwealth's official public access geospatial information clearinghouse (http://www.pasda.psu.edu/). Individual aerial frames from Erie County can be selected from an online imagery navigator tool. The photography used in this present study was dated 1 March 2006.

New York

The state of New York distributes digital aerial photography from its New York State Geographic Information Systems (NYSGIS) Clearinghouse. To trace recent bluff lines, this study used 1-foot (ft) resolution natural color imagery from April 2008. The aerial photography can be downloaded from the following web pages:

- Chautauqua County: http://www.nysgis.state.ny.us/gateway/mg/2008/chautauqua/
- Erie County: http://www.nysgis.state.ny.us/gateway/mg/2008/erie/.

Table 2 lists the coordinate system and other details about the 2008 photographs.

Table 2. Lake Erie orthophotography used as a basemap.

County, State	Date	Resolution	Format	Coordinate system
Erie, NY	April 2008	12 in.	JPEG 2000	State Plane NY West, NAD 83
Chautauqua, NY	April 2008	12 in.	JPEG 2000	State Plane NY West, NAD 83
Erie, PA	1 Mar 2006	12 in.	MrSid	State Plane PA North, NAD 83
All Ohio counties	Spring 2006	12 in.	MrSid	State Plane, OH North, NAD 83 HARN (U.S.feet)
	Sep 2009	0.3 m	Online	Served online from Esri Maps and Data

Notes:

1. NAD = North American Datum
2. For future analysis, online data served dynamically via Esri Maps and Data is more convenient than downloading aerial photographs. This also reduces file storage requirements.

Aerial photography--historical

Ohio

For late-1930s coverage, ODNR scanned 12 × 18 in. paper prints from the department's archives at 300 × 300 dots/in. (dpi) and saved them as TIFF files. Some of these frames were exposure- and contrast-enhanced with Photoshop Elements software to bring out subtle features.

Pennsylvania

Because 1938 digital bluff line data were already available, only a few frames needed to be downloaded and geo-referenced to plot the shoreline near Presque Isle and check the bluff interpretation near the Ohio border. The 1938 frames can be downloaded from Penn Pilot, an online library of historical aerial photography for the Commonwealth of Pennsylvania (http://www.pennpilot.psu.edu/).

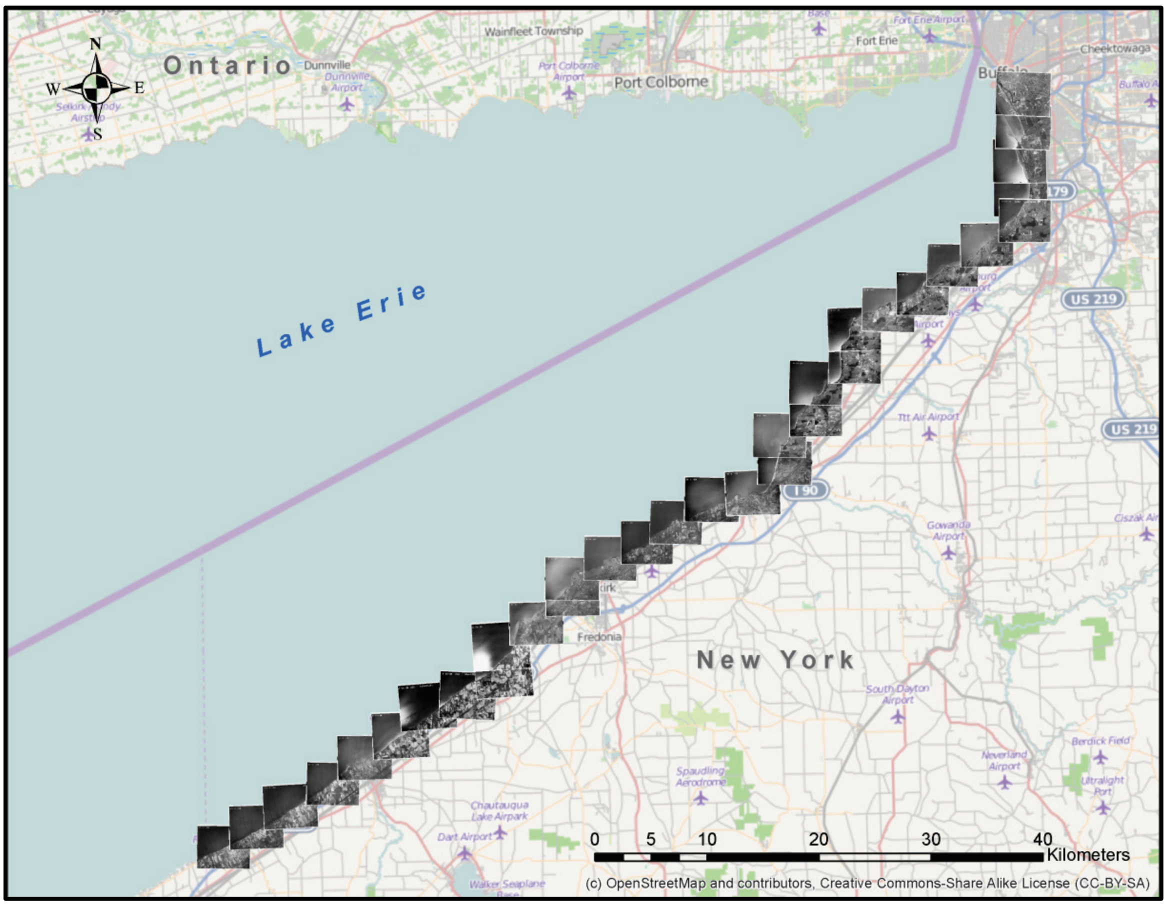
Pennsylvania Department of Conservation and Natural Resources (DCNR) supplied 1978 aerial photography in digital form. These were the same date and scale as the 1978s from New York and Ohio. The DCNR scanned the paper prints at 1,200 × 1,200 dpi and saved them as TIFF files.

New York

The ODNR supplied 1938 aerial photographs for New York State in the form of TIFF digital files (Figure 5). These were scanned from paper prints in the department's archives. Resolution of these photographs was approximately

1 to 2 m. Many were slightly blurred, possibly as a result of transfer from nitrate film stock to safety film by the National Archives. The original source of these photographs was the U.S. Department of Agriculture (USDA), Agricultural Adjustment Administration. The contractor may have been Continental Aerosurveys, Inc. of New York, NY. The 1930s photography was conducted as part of a pioneering program to improve conservation practices and precisely measure the nation's agricultural lands (Monmonier 2002). These frames were geo-referenced, and the bluff lines traced as per the procedure described in Chapter 4 of this document.

Figure 5. 1938 aerial photography in New York State. Resolution approximately 1 to 2 m. Imagery supplied by ODNR as TIFF files scanned from paper prints.



June 1978 photographs were retrieved from archives at Buffalo District or from Pennsylvania DCNR. These were scanned at 1,200 × 1,200 dpi and saved as jpeg files. These were geo-referenced and saved in the GIS project. Resolution was approximately 15 centimeters (cm).

For the westernmost 10 km of New York, the 1978 photographs were missing. A set of faded 1974 frames was used instead. The optical quality

was not as good as the 1978 photographs but was the only alternative from the 1970s for this area. The 1974 files were color enhanced and sharpened in Adobe Photoshop Elements software version 8.

Topography

U.S. Army Corps of Engineers (USACE) coastal charts

As stated previously, 1870s shoreline/bluff lines for New York or Pennsylvania were not available from any Federal or state agency. To plot a bluff line for this time frame, it was first necessary to geo-reference and digitize historical charts published by the Corps of Engineers as part of the "Survey of Northern and Northwestern Lakes." Buffalo District purchased copies of the 1870s charts from the National Archives and scanned them at 600 dpi to produce raster TIFF files.

Coast Charts Numbers 1, 2, and 3 were digitized for this project, extending from Buffalo to the Ohio-Pennsylvania border (Figure 6). Chart scale was 1:80,000. The charts farther west were not needed because ODNR supplied the Ohio 1870s bluff line.

Figure 6. Final transformation of 1870s Lake Survey Charts Numbers 1, 2, and 3 to UTM Zone 17 coordinate system. Background from Esri Maps and Data.

Contemporary lidar data

The USACE Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) collected topography and bathymetry data along the Lake Erie shore in 2006 using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. The NOAA Ocean Service, Coastal Services Center (CSC), distributes these data via an interactive web page. In terrain where tree cover obscured the bluff edge in the aerial photographs, the bare-earth-interpreted data with contour interval of 1 m helped delineate this boundary. This contoured topography was not necessary in pasture or cleared farmland, where the bare earth extended to the bluff edge and the edge was marked by a distinct shadow line.

Bathymetry

Contemporary lidar data

Lidar data acquired by JALBTCX were used to determine bathymetric conditions at Buffalo District harbors. Lidar was converted into a Triangulated Irregular Network (TIN) at each harbor and used as a modern basis for determining sedimentation (Figure 7). A TIN is a vector-based, three-dimensional (3D) representation of a surface, consisting of a set of irregularly distributed vertices (nodes) of a known elevation connected by a series of edges (break lines) to form a network of nonoverlapping triangles (Esri 2009).

USACE Buffalo District survey charts

Internal USACE survey charts were used extensively to fill data gaps in the lidar data and to determine historic bathymetry. Depending on availability, survey data were acquired digitally (either as an XYZ text file or as a scanned image of a chart) via microfiche or as an original paper chart (Figure 8). Survey charts dating as far back as 1866 were procured for this study. Any data not provided as an XYZ file was digitized and geo-referenced as necessary.

Figure 7. 2006 TIN at Fairport Harbor, OH. The TIN combines lidar data with 2006 USACE survey data.

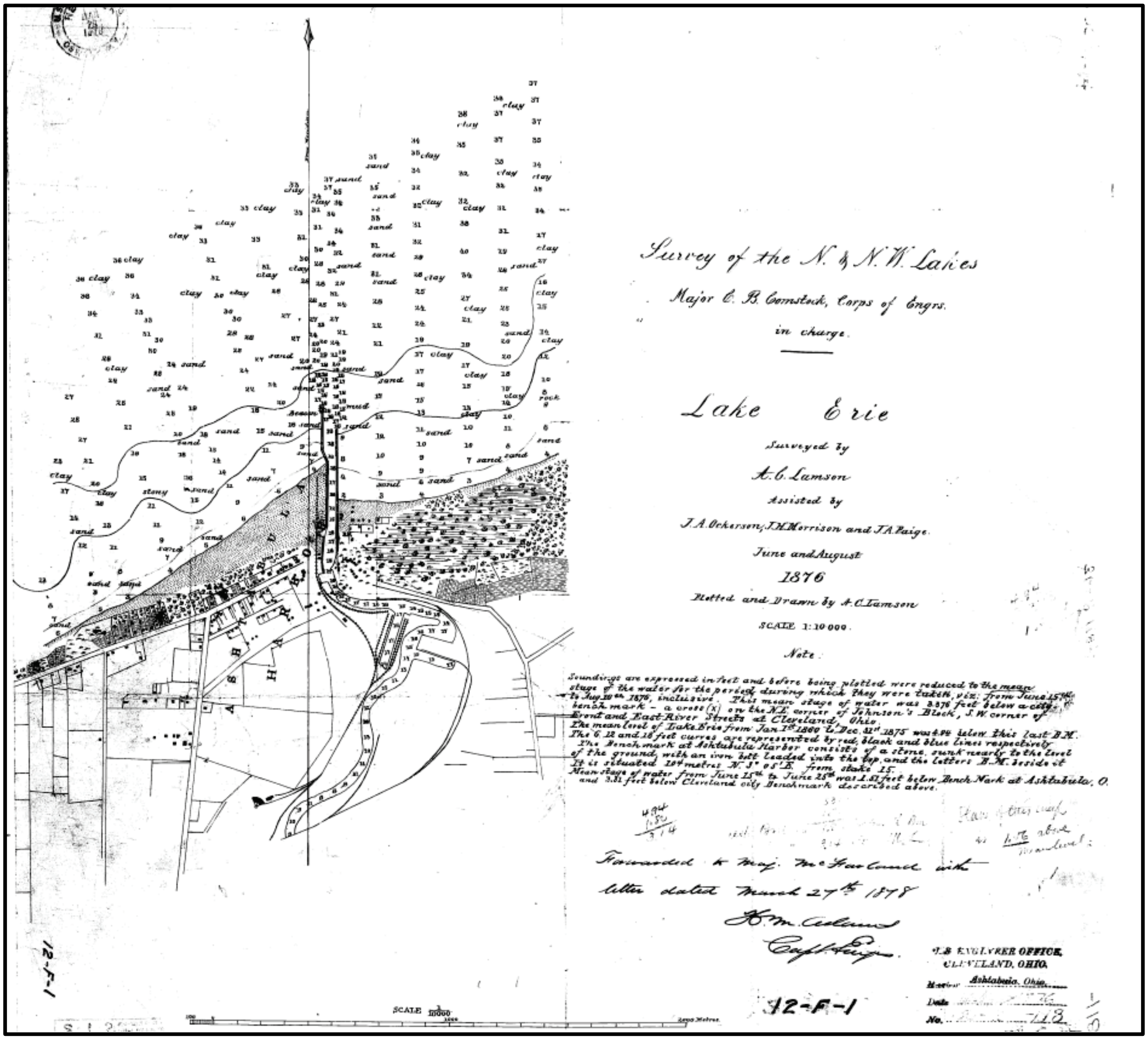
NOAA Great Lakes survey charts

Additional historical bathymetric data were acquired from the NOAA Lake Survey Charts. These charts were used as a secondary source, filling in gaps in the lidar and District surveys. Charts were downloaded as jpeg files, geo-referenced, and digitized.

Data display and software

All spatial and geographic data were organized and displayed in Esri ArcMap GIS software, versions 9.3.1 or 10.1. Data were projected in Universal Transverse Mercator (UTM) Zone 17N, North American Datum 1983 (NAD83), with units in meters. Lake Erie is in Zone 17N, and for multistate analysis, UTM allows data from multiple states to be displayed in the same projection.

Figure 8. 1876 USACE Survey Chart for Ashtabula, OH.



To visualize and develop the budget, the USACE Sediment Budget Analysis System for ArcMap (SBAS-A) software was applied (Dopsovic et al. 2002). SBAS allows modification to the budget as the study proceeds and more analysis is completed.

3 Bluff Line and Lacustrine Shoreline Mapping

Bluff line mapping 1870s—New York State

Chart geo-referencing

Because the 1870s T-sheets were raster image files, it was necessary to transform or geo-reference them onto a modern earth projection. The geo-referencing procedure required the following steps:

1. Import the T-sheet file into the ArcMap project.
2. Approximately fit the raster image to the study area.
3. Register known monuments marked on the chart to the correct latitude and longitude. For Chart No.1, the monuments were Tonawanda, West Base, Buffalo Plains, and Dunkirk Light. The locations in NAD83 coordinates were transcribed from National Geodetic Survey data sheets.
4. Identify man-made features on the raster file such as railroad bridges or street intersections that can also be clearly seen in the 2008 aerial photographs. Use the modern photograph to register the features on the 1880 chart. In some areas, it proved to be challenging to find common points because many roads have been relocated in the past 130 years and many farm fields have reverted to woodland or have been converted to suburbia.
5. Register one or two geographic coordinate positions on the upper regions of Charts Numbers 1, 2, and 3 to prevent the transformation from creating an unrealistic warped map image. The position of the latitude-longitude lines were not fully trusted to register the entire 1880 charts because charts of different vintages had lines scribed in slightly different positions. Nevertheless, using the geographic coordinates in the open water of the charts, even if in the wrong position by a few millimeters (mm), had minimal effect in the study area. The Ohio Geological Survey also did not use the latitude-longitude lines for their shoreline mapping[1].
6. Warp the raster file using the spline transformation. The spline transformation is a true rubber sheeting method and optimizes for local accuracy but not global accuracy. The spline transformation, with its emphasis on local accuracy, produced more realistic results in the vicinity

[1] Donald E. Guy, Jr., Ohio Geological Survey (retired), personal communication, 8 March 2010.

of the bluff and shoreline than the polynomial transformations. Table 3 provides the T-sheet geo-referencing with spline transformation.

Table 3. T-sheet geo-referencing with spline transformation.

Lake Survey Chart	Date Published	Monuments	Links	Total RMS error
No. 1, Buffalo, NY, to Dunkirk, NY	1880	Tonawanda, West Base, Buffalo Plains, Dunkirk Lighthouse	29	0.00002
No. 2, Dunkirk, NY, to Vicinity of Erie, PA	1878	Dunkirk Lighthouse, VanBuren Point	38	0.0064
No. 3, Erie, PA to Conneaut, OH, and Long Point, Ontario	1879	Erie Lighthouse	40	0.00003

Paper charts purchased from National Archives, scanned at Buffalo District at 600 dpi, and saved as TIFF files.

It is difficult to estimate geo-referencing error. The width of the line used to mark the shoreline, bluff line, or road-edge line is approximately 10 m on the 1870s charts. Main roads are drawn with width of approximately 25 m while the corresponding actual roads are only 10 m. The error of marking the position of the centerline on the modern aerial photographs was approximately 0.5 m but on the 1880 chart probably 2 to 3 m. Overall, an error of two pen widths or ±20 m is reasonable for these data. As a comparison, Woods Hole Group and Aubrey Consulting (2004) estimated that line width error representing the shoreline for 1864/1944 maps from Saco Bay, ME, to be ±12 m (±40 ft).

Bluff line tracing and accuracy

Once Charts Nos. 1, 2, and 3 were transformed, the shoreline or bluff line was traced manually (on screen) at a scale of approximately 1:5,000.

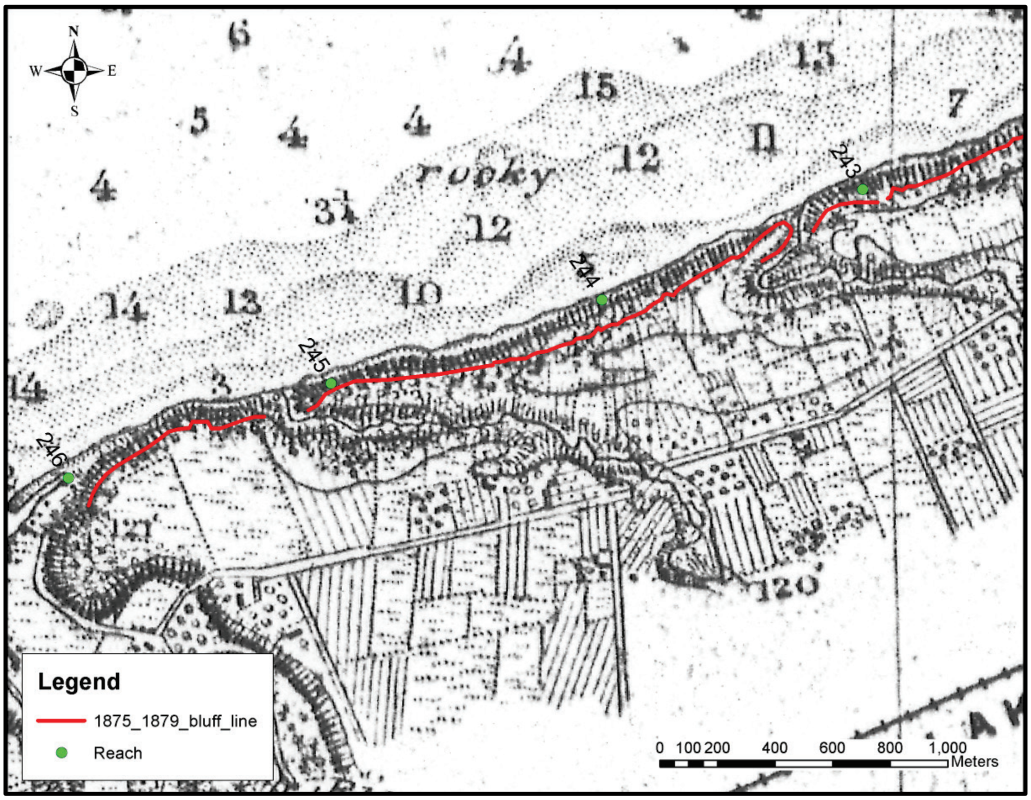
On Chart No.1, the draftsman drew the bluff line as a single distinct line. The width of a printed line was approximately 10 m, so the best possible accuracy here was ±10 m.

On Chart No. 2, the position of the bluff top was shown as a fuzzy line with cross-hatching. The bluff edge was usually interpreted to be along the center of the cross-hatching after being aided by modern photographs and the 1938 bluff line.

On Chart No. 3, the cross-hatching was less distinct. It is unclear if the original topographers measured a separate shoreline and bluff line or just

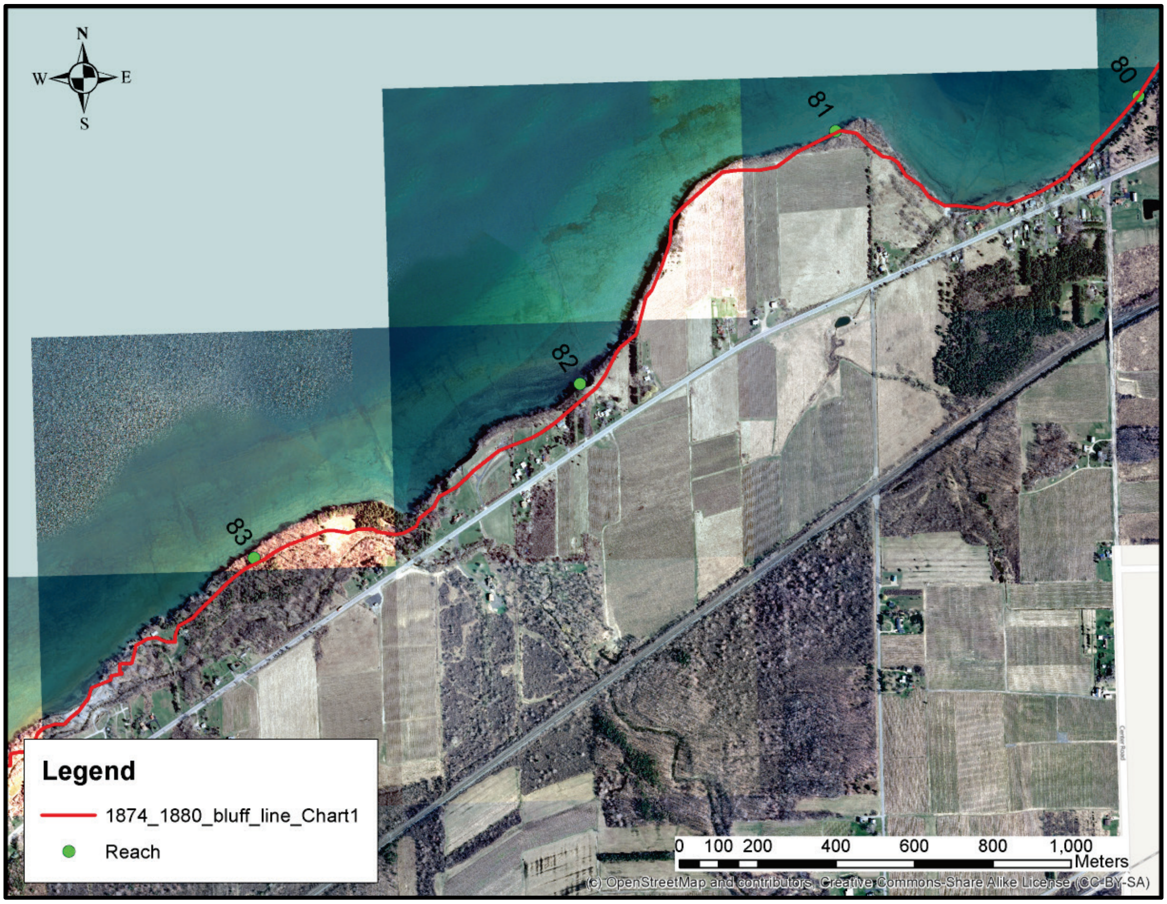
measured the shoreline and drew hatch-lines to show the existence of a sloping bluff. Along much of the shore between the New York state line and Erie, PA, the bluff line was interpreted to be approximately mid-way along this indistinct shore-bluff zone. Accuracy here realistically is ±20 m. West of Presque Isle, the cross-hatching was wider, and the top of the bluff was interpreted closer to the landward (south) edge of the marks. Figure 9 is an example near Elk Creek in western Pennsylvania.

Figure 9. Example of bluff line interpretation in western Pennsylvania near Elk Creek, Lake Survey Chart No. 3, 1879 publication. Water depths change from feet near the shore to fathoms offshore.



The major source of error in this mapping effort is a result of topographic features that were incorrectly drawn on the 1870s charts. Some of the till headlands on these charts do not project into the lake as far as they do in the 2008 photography. No contemporary geological mechanism can create till bluffs. There was no obvious cause for this error related to tracing the shore or transforming the charts. As an example, Figure 10 shows the 1874 shoreline superimposed on the 2008 photographs just east of Dunkirk, NY. The 1874 bluff line between reaches 81 and 83 is erroneously south of the modern bluff.

Figure 10. 1874 bluff line east of Dunkirk, NY. In this example, the 1874–1880 line is erroneous because it should be lakeward of the bluff in the 2008 photographs.



Bluff line mapping–1930s and 1970s aerial photography

Photograph transformation

The procedure for transforming raster photographs was similar to the procedure used for the 1870s Lake Survey charts. It consisted of identifying common points between the historical photographs and the 2000s aerial photographs (2008 for New York, 2006 for Pennsylvania, 2009–2011 for Ohio). Reference points included sidewalk intersections, monuments, fountains, walkways, some major in-water features like breakwater stones, and some corners of prominent buildings such as schools.

Transformation accuracy was estimated to be ±10–15 m for the 1938 photography and ±10 m for the 1970s photography. In a similar study of historical aerial photography along the Southern California Bight, Orme et al. (2011) also estimated that accuracies associated with rectification fell within ±10 m

root-mean-square (RMS). They noted that source errors include photograph distortion, scale, scanning issues, and rectification difficulties.

Bluff line tracing

The bluff edge was interpreted from geo-referenced aerial photographs (1938 for New York and Ohio; 1978 for New York and Pennsylvania). In some areas, 1 m contours based on topographic lidar surveys provided extra verification of the visual interpretation. Three degrees of ground cover were present:

1. Farm or lawn with grass mowed to the bluff edge: Here the interpretation was straightforward.
2. Intermittent tree coverage: The interpretation consisted of identifying the bluff edge at bare ground areas and drawing the line from one bare area to the next.
3. Complete tree coverage: The last sun-lit trees at the crest of the bluff were identified and the line drawn approximately through the middle of these trees. In some areas, subtle changes in gray tone or foliage type marked the bluff edge. Interpretation was aided with lidar-based contours.

Shoreline mapping--Ohio shore west of Catawba Island

West of the Marblehead Peninsula and Catawba Island, the coastal morphology changes to a low lacustrine muddy/sandy terrain. Therefore, for mapping shoreline change, a low shoreline had to be defined in contrast to the bluff edge used along the eastern portion of the lake.

When the Ohio Geological Survey mapped this area in the past, they developed a set of administrative rules to maintain a standard procedure. In all cases, they tried to find a geomorphic mark that represented a semi-permanent feature they could define as *shoreline*[1]. The Ohio Geological survey did not adjust for lake level. They considered a geomorphic feature such as a wave-cut scarp, vegetated dune, or a tree line to be a more representative shoreline at the time a photograph was taken. For this present study, the following features were interpreted as a shoreline:

1. Prominent light/dark line where light represented a sand/mud beach while dark was a more permanent feature like vegetation.

[1] Donald Guy, ODNR, Division of Geological Survey (retired), personal communication, 11 July 2012.

2. Tree or vegetation line.
3. Prominent scarp.
4. Man-made feature like a revetment or harbor wall. These were much less common in 1938 compared to the 1970s and later.

Accuracy was estimated to be ±10 m.

4 Bluff Line and Shoreline Change

Digital Shoreline Analysis System (DSAS)

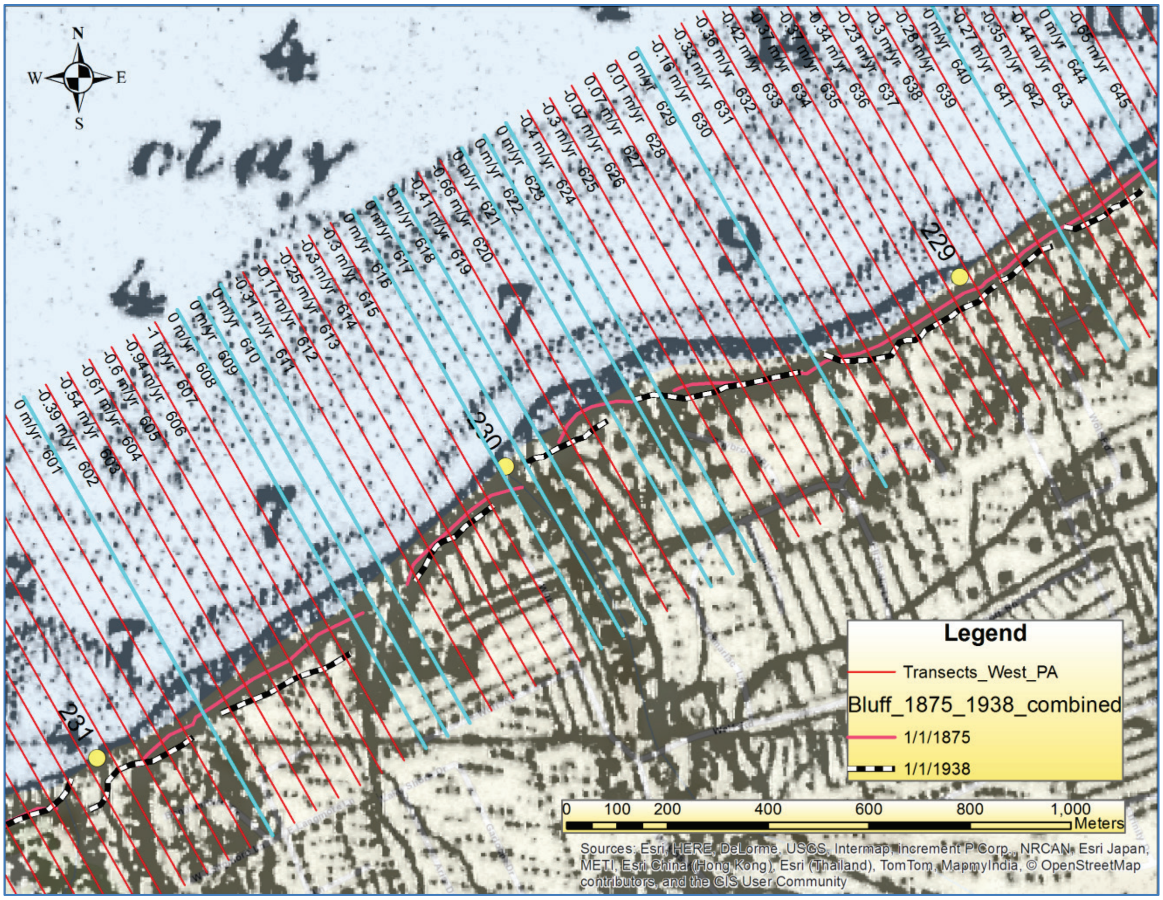
The USGS ArcGIS extension known as the Digital Shoreline Analysis System (DSAS), initially Version 3 and later Version 4, was used to calculate bluff line or shoreline change rates. USGS Open File Reports 2005-1304 and 2008-1278 describe the theory and procedures for DSAS (Thieler et al. 2005, 2009).

Calculating bluff recession statistics requires several steps:

1. Draw a baseline parallel to the shoreline.
2. Select a transect interval. In this present project, a 50 m interval provided 20 transects per 1 km reach. The DSAS program draws transects perpendicular from the baseline.
3. Select pairs of bluff edge shape-files (1878/1879–1938, 1938–1978, 1978–2006/2007).
4. Modify the attribute tables of each shape-file to include a date field with the numeric date in the form of <mm/dd/yyyy>.
5. Select input options for calculations (baseline, transect length, etc.).
6. Generate recession rate for each date pair with the Calculate Statistics button .
7. In the Source menu of the ArcMap project, open the table of rates generated by the calculation procedure. Export the table to an Excel spreadsheet.

Not all transects could be used for shoreline measurements. First, each transect must intersect bluff lines for two dates. Second, transects where the older shape-file was landward of the newer date were rejected. Because there is no contemporary mechanism that can recreate glacial till deposits, till bluffs can only remain stable or recede, and younger bluff lines must be at the same location or landward of older bluff lines. As described earlier, the 1870s maps showed erroneous bluff lines and shorelines in some areas. For these transects, the data were removed (i.e., would not be used in the calculation of average recession in the reach). The averaged recession rate for each 1 km reach was entered in the master calculation spreadsheet. An example of cross-shore transects calculated by DAS software is shown in Figure 11.

Figure 11. Example of cross-shore transects calculated by DSAS software near Reaches 229 and 230 in western Pennsylvania. Red lines show transects that intersect recession lines for 1875 and 1938. Non-intersection returns a result of 0.0 m/year change.



The End Point Rate (EPR) method was used to compute the recession rate (Theiler et al. 2009). Because the differences in recession for the three time segments were being evaluated, the DSAS software was not used to evaluate an overall recession (1870s–2000s) via linear regression or weighted linear regression. This latter method is appropriate to an environment where the study requires one number to categorize shoreline advance or recession over the entire study period.

Ohio bluff lines and shorelines

The ODNR developed cross-shore transects at approximately 30 m intervals (100 ft originally) from which they computed historic shoreline retreat. The original mapping was conducted optically from 1848, 1870s, and later coast charts or T-sheets with transects drawn on Mylar transparencies. These transects were designed to provide a legal basis for various Ohio management uses and in many areas, included calculations

made across harbor fillets and other low terrain. Therefore, for this present project, the ODNR transects were not used; instead, new baselines were drawn, and DSAS was used to compute recession statistics.

5 Sediment Accumulation at Harbors Based on Historic Bathymetric Data

Bathymetric data were acquired at Buffalo District harbors to determine the magnitude of sediment accumulation since the construction of the harbors. Sediment changes have been computed at the following locations.

1. Port Clinton Harbor, OH
2. West Harbor, OH
3. Huron Harbor, OH
4. Fairport, OH
5. Lorain, OH
6. Geneva-on-the-Lake, OH
7. Ashtabula, OH
8. Conneaut, OH
9. Barcelona, NY
10. Dunkirk, NY
11. Cattaraugus Creek, NY

Sediment accumulation within and adjacent to each harbor was computed using a combination of lidar data acquired in 2006 and 2011; aerial images from 1938, 1974, 2006, and 2007; a series of Buffalo District historic drawings ranging from 1866 to 2006; and historic navigation charts retrieved from NOAA (http://historicalcharts.noaa.gov/). All elevations were converted to the IGLD85 vertical datum based on the work of Gardner (1875), Lippincott (1985), and USACE (1940). This involved converting data from NAVD88, IGLD55, USLS 1935, NGVD29, USLS 1903, Mean Level of Lake Erie (1860–1875) (Toledo-Conneaut), Mean Lake Level of Lake Erie (1860–1875) (Erie-Buffalo), and Mean Lake Level of Lake Erie (1844–1857).

As the 2006 lidar data were reported in elevation NAVD88, datum conversions were made during this present study for each harbor using NOAA's VDATUM vertical datum transformation software (http://vdatum.noaa.gov/). Because elevations were reported on historic charts as soundings from the respective datum, the soundings were imported into ArcGIS and then subtracted from the appropriate converted water datum as listed in Table 4.

Table 4. Base elevations used for datum conversion (based on work by Gardner [1875], Lippincott [1985], and USACE [1940]).

Datum	LWD IGLD85 (m)
Mean Lake Level, 1844–1857	174.19
Mean Lake Level, 1860–1875, Toledo-Conneaut	174.09
Mean Lake Level, 1860–1875, Erie-Buffalo	174.12
U.S. Lake Service Low Water Datum of 1903	173.58
U.S. Lake Survey, 1935	173.5
International Great Lakes Datum, 1955	173.5
North American Vertical Datum, 1988	Varied based on location

Base bathymetric conditions were determined from the USACE Survey Charts. The charts cover conditions from deep water up to the shoreline and were pulled from preconstruction surveys where available; otherwise, the earliest available survey was used. These data were digitized into ArcGIS and used to create a triangulated irregular TIN. All TIN creation was accomplished with Esri's ArcGIS 3D Analyst software.

Additional TINs were created for the years 1938, 1974, and 2006 to measure sediment deposition/erosion patterns due to the construction of harbor structures (piers and breakwaters). Where harbor structures had been constructed that were likely to cause significant changes to longshore transport (e.g., a shorearm constructed at Ashtabula Harbor, OH, in 1922), an additional TIN was created representing conditions at the time of construction. This allowed for determination of sedimentation rates pre- and post-construction.

Outside of the Federal channels, high-resolution bathymetric data were not available at most harbors for the 1860s, 1930s, and 1970s time frames. These areas, especially on the updrift side of the harbor, were often the sites of the greatest sedimentation. To facilitate TIN creation for these areas, a method of shoreline regression was performed at the largest harbors, utilizing the historic shoreline positioning and the contemporary lidar data. For this process, it was assumed that the basic cross-shore profile at a harbor had remained consistent over time but had shifted in space lakeward as sedimentation occurred. Using historic aerial imagery, the position of the shoreline at previous time-steps (1970s, 1930s, and 1860s) was digitized and normalized to a consistent water level based on the local foreshore slope and water levels at the time of the image (Tides and Currents 2015). A series of transects spaced 50 m apart was set up

over the modern TIN, and an XYZ value was determined at 1 m spacing along these transects (Figure 12). The XY location of each point was then shifted backwards along the transect by an amount equal to the shoreline change, giving a shifted XYZ position. This position was adjusted where necessary based upon the location of the bedrock bluff and the basal elevation of the bedrock underlying the fillet, where known or inferred. These computations were carried out using a program running in Microsoft Excel software. Finally, historic NOAA charts were used to confirm and fill in data.

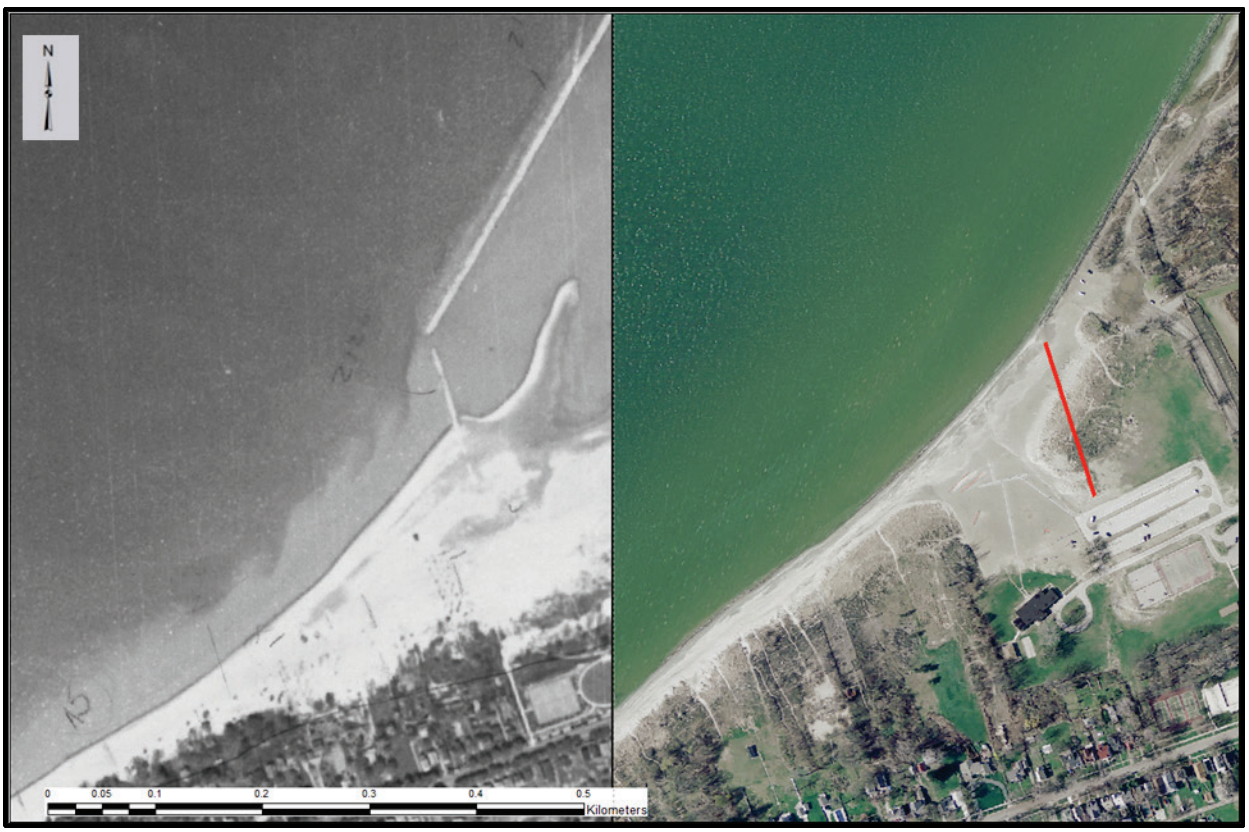
Figure 12. Shorelines (normalized to LWD +2 ft) and transects at Fairport Harbor, OH.

Once the TIN surfaces were created, the ArcGIS TIN Difference tool was utilized to determine volumetric changes between successive time periods. TIN Difference functions in the vector domain by creating a third temporary TIN from the height difference between nodes and breaklines of the two input surfaces. Zero contours in this difference TIN are added as break lines, and triangles are classified as either above, below, or equal to a value of 0.0. The tool then groups contiguous triangles, summing their volumes and writing these volumetric contributions to a polygon feature

class. This polygon feature class thus contains areas where the second (older) TIN is above the first (counted as volume loss), below the first (counted as volume gain), or is coincident with the first (no change). Summing the losses and the gains gives a net volume change between the two surfaces (Esri 2010).

Where necessary, the breakwaters were modeled into 3D surfaces, and the volume of each structure was determined. Determining the breakwater volume was necessary where the breakwater had been partially or fully buried in sediment (Figure 13). These volumes were subtracted from the total volume computations resulting from the TIN difference analysis to ensure that the computed volumes were for sediment deposition only.

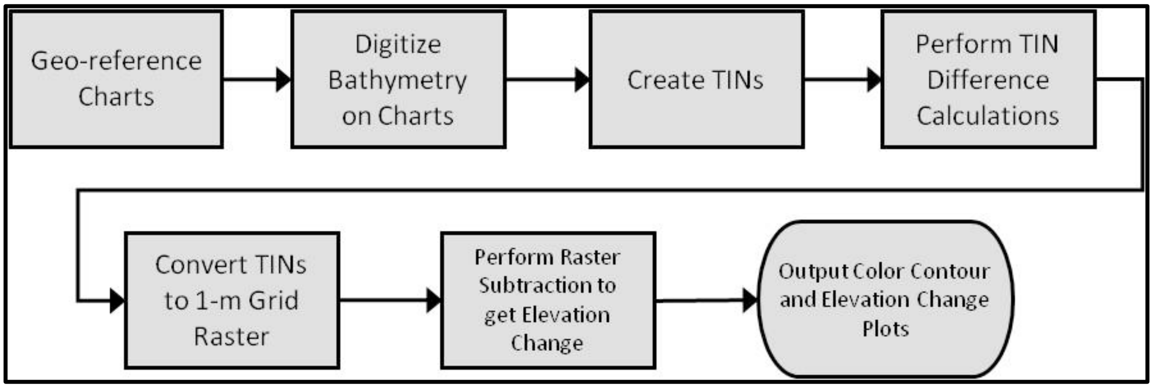
Figure 13. Ashtabula, OH, 1938–2006. Red line in modern image represents location of the now-buried Shorearm Breakwater (constructed 1924).



The TIN Difference tool was run between each of the time periods, giving a complete picture of sediment change patterns at each harbor. By dividing the volumetric change by the total area of analysis, an average elevation change across the project area was determined. Additionally, for visualization purposes, each TIN was converted into a raster image

consisting of 1 m pixels. The older raster was then subtracted from the newer raster, resulting in an elevation change map throughout the project area. Figure 14 shows a simplified flowchart of the computation process.

Figure 14. Simplified computation process.



6 Sediment Budget

Sediment budget littoral cells

A sediment budget is a tallying of sediment gains and losses, or sources and sinks, within a specified control volume (cell) or series of connecting cells over a given time frame. Cells are defined by geologic features or natural geomorphic boundaries, data resolution, coastal structures, and knowledge of the site. Sediment may pass from one cell to another, either naturally by wave and current-induced transport or artificially via dredging and placement. Rosati (2005) provides a more complete description of sediment budget methodology.

The basic sediment budget equation can be expressed as

$$Q\,source - Q\,sink - \Delta V + P - R = Residual \tag{1}$$

where:

Q_{source} and Q_{sink} = the sources and sinks to the control volume, respectively
ΔV = the net change in volume within the cell
P = the amount of material placed in the cell
R = the amount of material removed from the cell
Residual = the degree to which the cell is balanced.

For a balanced cell, the residual is zero. For a region consisting of many contiguous cells, the budgets for individual cells must balance to achieve a balanced budget for the entire regional system.

Sediment gains and losses that may apply to a Lake Erie budget cell are summarized in Table 5. Aeolian transport now is a lesser factor in the Lakes than along many ocean beaches, although before 1800s development, southern Lake Michigan had extensive dunes.

Table 5. Sediment gains and losses for budget calculation.

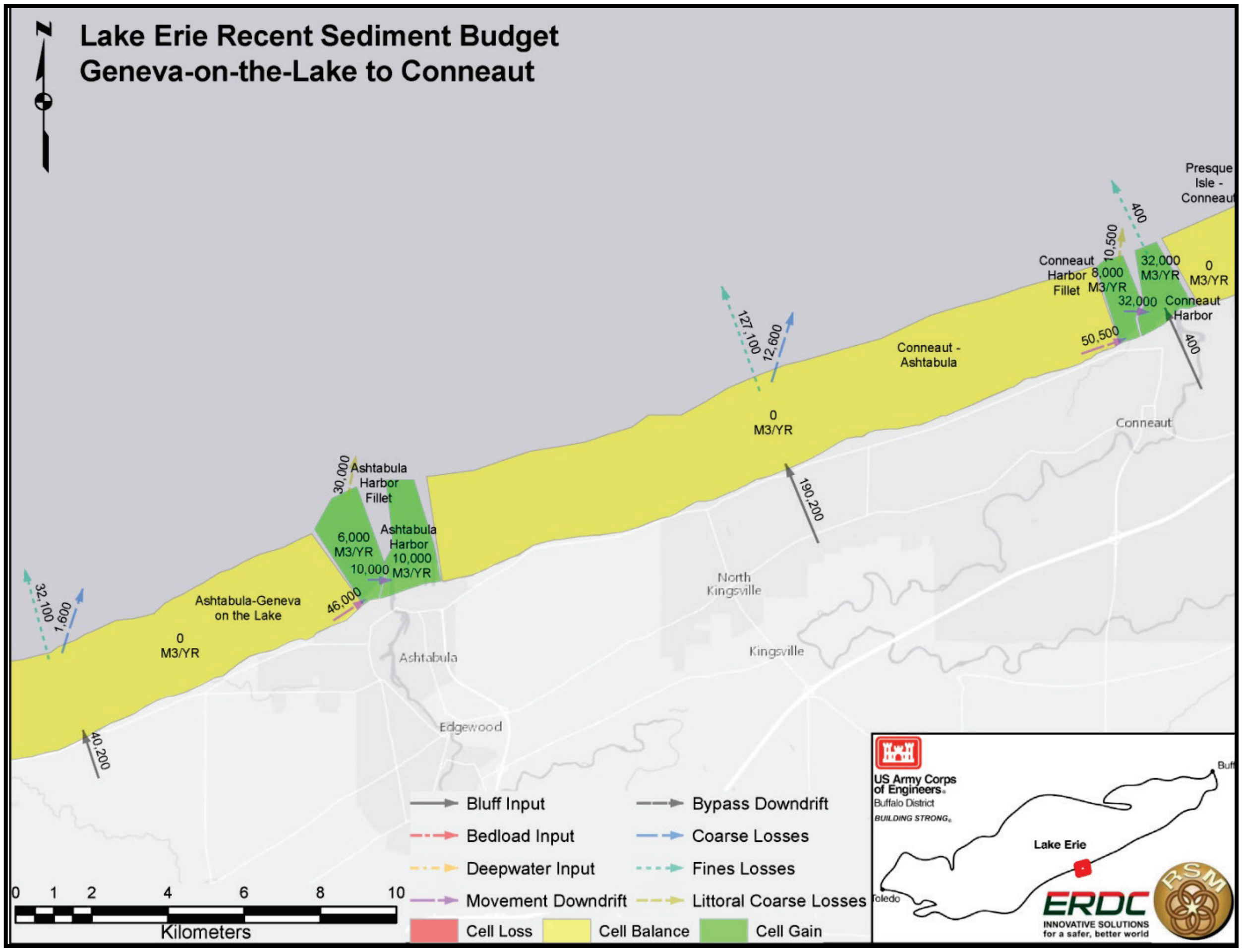
Gains	Losses
Longshore transport into cell	Longshore transport out of cell
Riverine supply	Offshore transport (to deep water)
Bluff erosion	Aeolian transport inland or out to lake
Aeolian transport onto the beach	Transport into dredged navigation channels
Onshore transport	Beach mining or other anthropogenic causes (unknown volumes historically)
Beach nourishment	
Dumping of debris	

For this present study, the primary flux into the system is bluff erosion (ΔV) and includes both the fine (silt and clay) fraction as well as coarse (sand and gravel). Loss of fine grain sediment offshore is a flux out of the cell (shown as arrows pointing out into the lake). Owing to the shorter fetch over which waves can build, shoreline processes are dominated by the higher amplitude, shorter wavelength erosive storm waves. Based on this hydrodynamic setting, the present study assumes an additional loss of 20% of the coarse sediment contribution from the bluff to deep water. This value comes from the sediment budget developed for the Presque Isle Beach Nourishment Project in Erie, PA, in USACE (1984). Artificial sediment movement out of the cell, such as the bypassing at North East Marina, is shown as a flux out of the cell representing a positive number for the term R. Artificial placement, such as at the cell east of North East Marina, is entered as a positive number for the term P.

For most of the Lake Erie shore, cell boundaries are defined by harbor structures, which have functioned as littoral barriers since the early to mid-1800s. Updrift of the largest of these harbors, a substantial fillet has accumulated since construction. For clarity, additional cells are defined to delineate this accumulation (Figure 15). Additional cells were created at known nodal points in the general transport direction as identified by ODNR (2007) (Figure 16).

If a substantial fillet has accumulated on the updrift side of a harbor structure, the modern extent of the fillet defines another cell (for example, the cells just east of the Ashtabula and Conneaut Harbors in Figure 15).

Figure 15. Example of sediment budget between Geneva-on-the-Lake and Conneaut, OH. Littoral cells represent a geomorphic unit of bluff, beach (if existent), and nearshore. Arrows represent fluxes into and out of each cell. Cell symbology is determined by the net change in littoral cell volume. The full SBAS outputs are provided in Appendix B.



Each littoral cell represents a geomorphic unit that includes bluff, beach, and the shallow nearshore zone (representing the active zone, or approximately less than 10 m water depth). The dimension alongshore represents the linear extent of the cell, but the shore-perpendicular width does not represent a specific value or dimension. The depth of the nearshore zone is unspecified, and cells have been drawn with exaggerated cross-shore dimension for display purposes. Table 6 lists the littoral cells needed to represent the southern Lake Erie littoral system.

Figure 16. Sand transport map of Ohio (ODNR 2007).

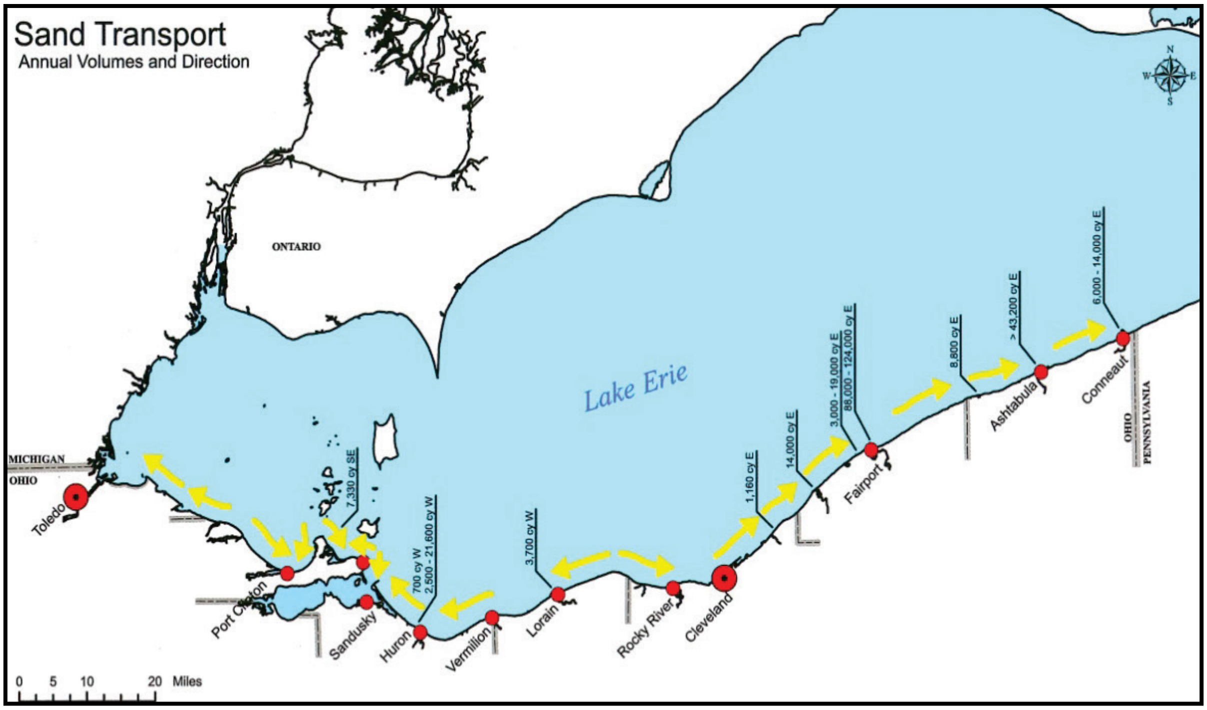


Table 6. Lake Erie littoral cells (listed west to east).

Cell #	Cell Name	Cell #	Cell Name
1	Toledo-Cooley Canal	19	Lorain Harbor West
2	Cooley Canal Harbor	20	Lorain Harbor East
3	Cooley Canal-Locust Point Nodal Point	21	Lorain-Domonkas Library
4	Locust Point Nodal Point-Port Clinton	22	Domonkas Library
5	Port Clinton Harbor	23	Domonkas Library-Avon Lake
6	Port Clinton-Catawba Island Nodal Point	24	Avon Lake
7	Catawba Island Nodal Point-West Harbor	25	Avon Lake-Avon Lake Nodal Point
8	White City Park	26	Avon Lake Nodal Point-Rocky River
9	West Harbor-Marblehead Nodal Point	27	Rocky River Harbor
10	Marblehead Nodal Point-Sandusky	28	Rocky River-Cleveland
11	Sandusky-Huron	29	Cleveland Harbor Fillet
12	Huron Harbor	30	Cleveland Harbor
13	Huron-Vermilion	31	Cleveland-White City Park
14	Vermilion Harbor	32	White City Park
15	Vermilion Harbor Fillet	33	White City Park-Cleveland Lakefront St Park
16	Vermilion-Beaver Park Marina	34	Cleveland Lakefront St Park
17	Beaver Park Marina	35	Cleveland Lkft St Park-Eastlake PP
18	Beaver Park Marina-Lorain	36	Eastlake Power Plant Fillet

Cell #	Cell Name	Cell #	Cell Name
37	East Lake Power Plant	60	Shades Beach-Crittenden Point
38	Eastlake Power Plant-Mentor Harbor	61	Crittenden Point-North East Marina
39	Mentor Harbor Fillet	62	North East Marina Fillet
40	Mentor Harbor-Fairport	63	North East Marina
41	Fairport Harbor Fillet	64	North East Marina-Twenty Mile Creek Point
42	Fairport Harbor	65	Twenty Mile Creek Point-Barcelona
43	Fairport-North Perry	66	Barcelona Fillet
44	North Perry Marina	67	Barcelona Harbor
45	North Perry-Geneva-on-the-Lake	68	Barcelona-Van Buren Point
46	Geneva-on-the-Lake Fillet	69	Van Buren Point-Dunkirk
47	Geneva-on-the-Lake	70	Dunkirk Outer Basin
48	Geneva-on-the-Lake-Ashtabula	71	Dunkirk Harbor
49	Ashtabula Harbor Fillet	72	Dunkirk-Fletcher Point
50	Ashtabula Harbor	73	Fletcher Point-Silver Creek
51	Ashtabula-Conneaut	74	Silver Creek
52	Conneaut Harbor Fillet	75	Cattaraugus Fillet
53	Conneaut Harbor	76	Cattaraugus
54	Conneaut-Presque Isle	77	Cattaraugus Scour
55	Presque Isle	78	Cattaraugus Shoal
56	Gull Point	79	Cattaraugus-Sturgeon Point
57	Erie East Fillet	80	Sturgeon Point Fillet
58	Erie-Shades Beach	81	Sturgeon Point
59	Shades Beach	82	Sturgeon Point-Buffalo

7 Sediment Budget Littoral Fluxes

Flux lines are vector-based representations of sediment movement within SBAS. They must begin or end within a littoral cell, and the direction they are drawn indicates the positive direction of sediment movement. Fluxes that begin in a cell and end outside of any other cells are net sinks from the system, while the reverse shows net gains into the system.

Bluff recession is the primary source of material input into the system. Secondary sources are beach nourishment (at Presque Isle State Park) and riverine bed load. The largest source of riverine sediment within the study area is Cattaraugus Creek, where a flux of 2,700 m^3/year (3,500 yd^3/year) is modeled, based on USACE (1976). Additional sources of riverine load are likely, but definitive coarse fraction quantities are not available. Bluff recession is annotated within the sediment budget by an arrow directed from onshore into each littoral cell. The bluff recession input volume represents both the coarse and fine fraction of material resulting from erosion. Of this, the fine fraction is presumed to be lost from the system to deep water, represented by the arrow running approximately perpendicular to the cell into deep water. Additionally, 20% of the coarse fraction is assumed lost to deep water beyond the depth of effective sediment transport as a result of short-period storm waves. This volume is represented by an arrow running obliquely from the cells into deep water.

Two additional sediment sinks from the system are modeled. At harbors with a well-developed fillet (Conneaut, Fairport, and Ashtabula, OH), the sediment is moved along the fillet by wave action and eventually diverted into deep water at the lakeward end of the coastal structures. Along the eastern Pennsylvania/New York coast, a series of headlands extend out into the lake. At these headlands, some littoral material is carried around the headland and continues in the system while the remainder is lost to deep water (Figure 3). At each of these headlands, a percentage of material is removed from the system (Table 7). These losses were determined based on the geometry of each of the headlands, and additional study is necessary to refine and verify these values. An example of the sediment budget visualization is shown in Figure 15.

Table 7. Littoral cell sediment losses at headlands (in percent).

Sturgeon Point	25
Silver Creek	10
Fletcher Point	10
Point Gratiot (Dunkirk)	50
Van Buren Point	50
Barcelona	50
Twentymile Creek	25
Crittendon Point	50

8 Measurement of Sediment Derived from Bluffs and Beaches

Determination of stratigraphy of bluffs

Ohio

ODNR supplied cross sections of coastal stratigraphy. Some of the cross sections had been published (Pavey et al. 1995; Stone et al. 1995, 1996), while others were unpublished hand-drawn diagrams on cross-section paper. Appendix A reproduces cross sections from Stone et al.[1], covering the Ohio shore from Avon Point to the Pennsylvania border. The cross sections were marked with transect numbers, but these transect numbers are not the same as the contemporary Ohio cross-shore transects, and it was not possible to establish locations using these numbers. Instead, the individual sections were fitted into their appropriate location along the shore within ArcMap, using rivers and prominent geographic features as the boundaries (Figure 17).

Eastern Ohio presented a challenge to determining stratigraphy and recession. From approximately Port Clinton through Toledo, there is little to no bedrock bluff exposed. The sediments in this area consist primarily of highly erodible lacustrine silts and clays deposited by old glacial lakes (ODNR 2007), interspersed with occasional lenses of beach sand.

The shoreline bluff height and composition were generated through a combination of JALBTCX bare earth processed lidar and U.S. Department of Agriculture (USDA) Soil Survey Data (Natural Resources Conservation Service, Soil Survey Geographic (SSURGO) Database), (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). These surveys contain a wide range of soil attributes, including a typical profile and parent material. The soil data are downloadable by county and consists of a polygon shape-file associated with a document containing the relevant symbols and descriptions.

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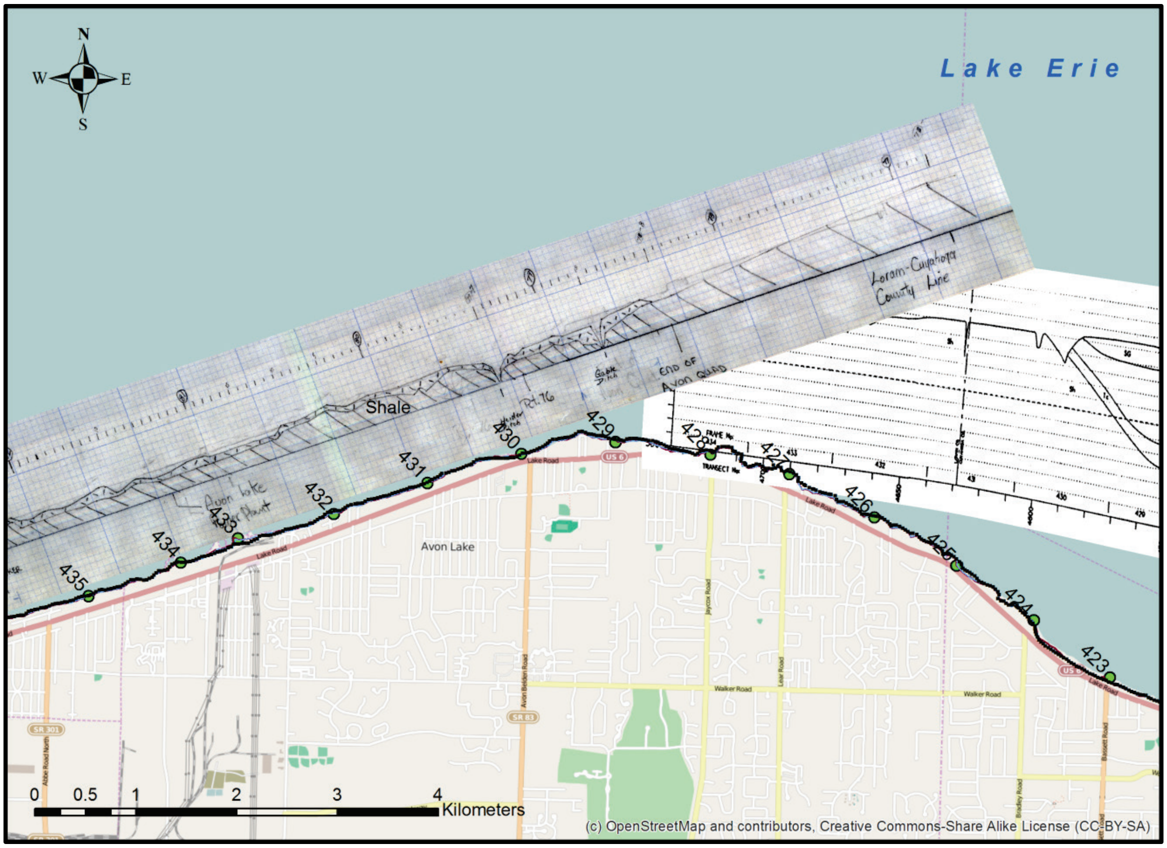
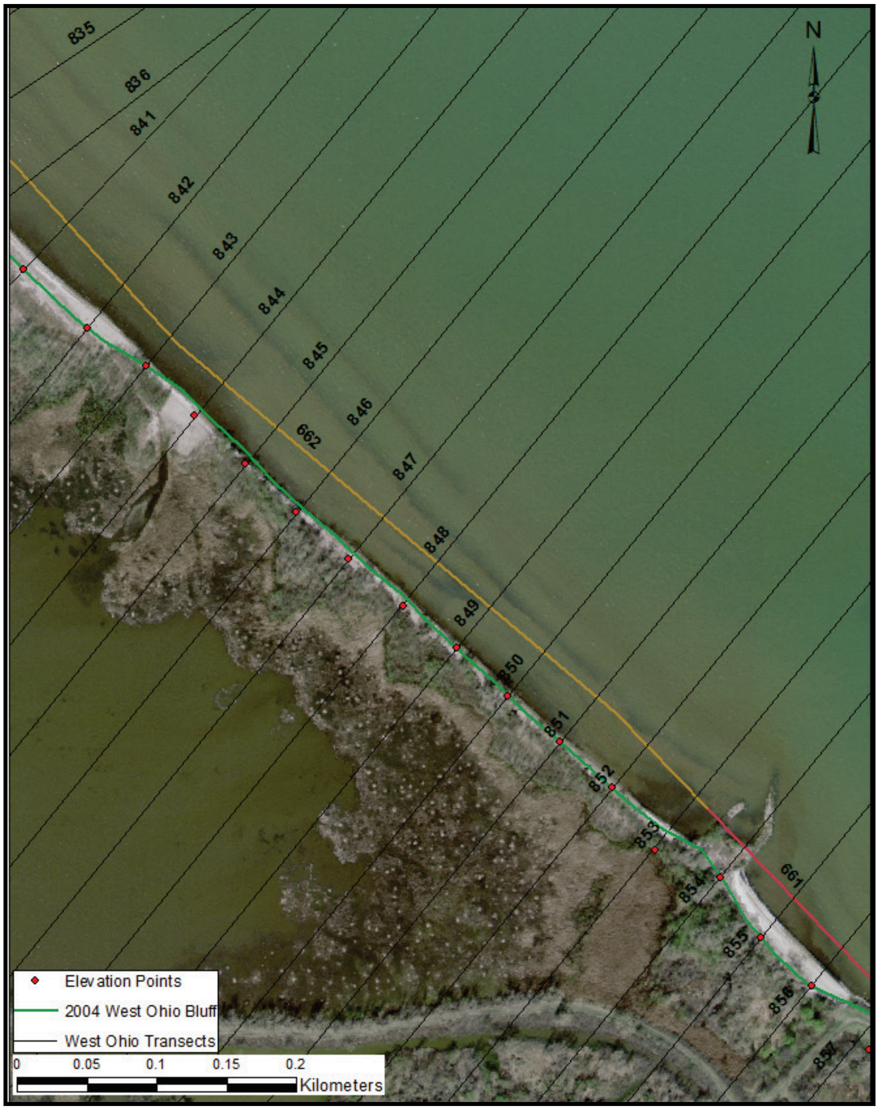
[1] Stone, B. D., R. R. Pavey, J. A. Fuller, and D. S. Foster. Unpublished report. Map of surficial surface materials in the Lake Erie coastal area, northeastern Ohio. U.S. Geological Survey Open-File Report. Denver, CO: U.S. Geological Survey Publications Warehouse.

Figure 17. Example of Ohio bluff stratigraphy cross section fitted to the correct location along the coast, based on towns, creeks, and topographic features.



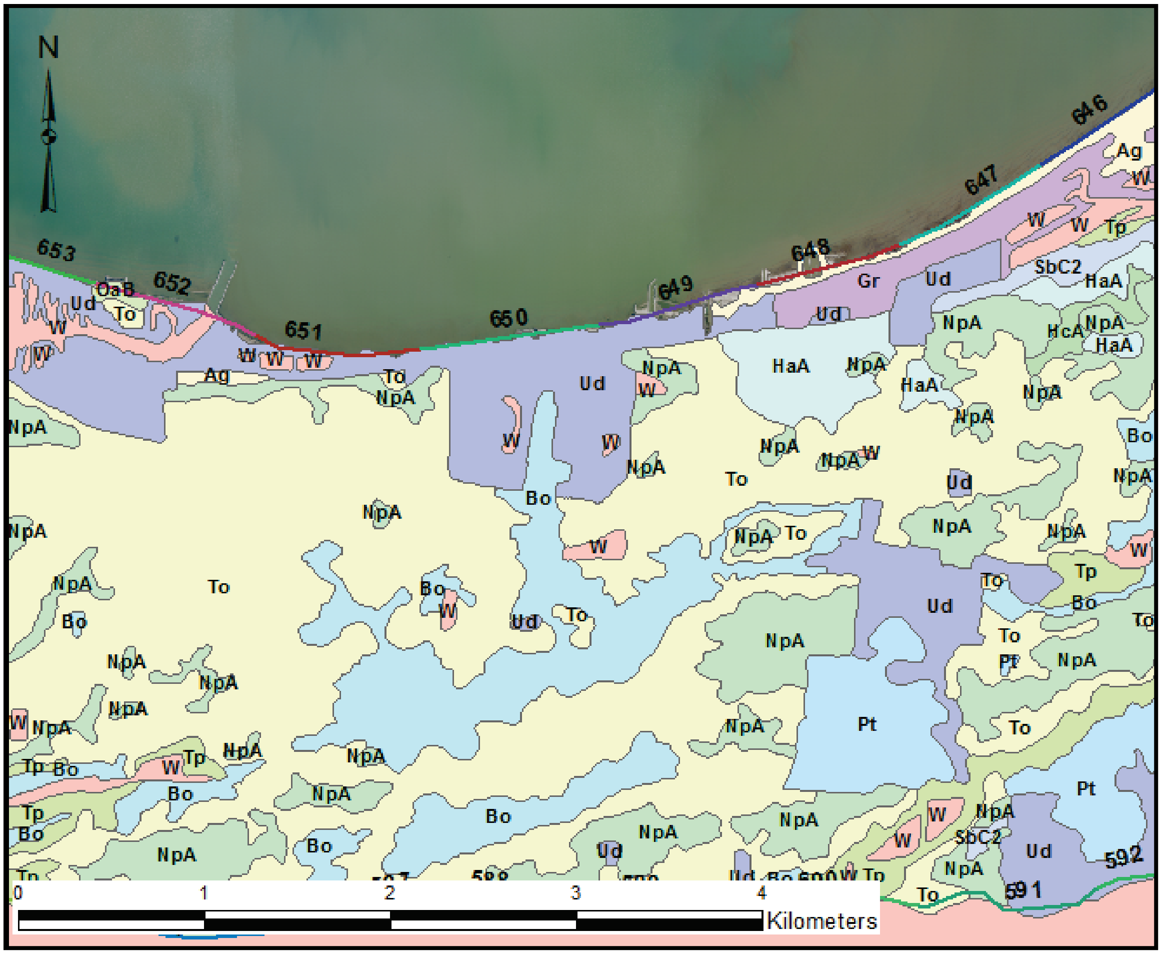
To determine the bluff or recession line feature elevation, the Intersect tool in ArcMap was run to provide a map of the intersection of the most modern bluff line with each of the transects generated by DSAS. These intersection points were then joined to the 1 km reaches to write the appropriate reach for each point to the attribute table. These points were manually adjusted or removed where necessary to a surface that approximately represented the bluff elevation for that transect. Once the points were positioned properly, elevation data were written to the points from the bare earth lidar data using the Add Surface Information tool. Transects within each 1 km reach were then averaged to give an average elevation over the reach. A section of the West Ohio low shoreline is displayed in Figure 18, with transects, the 2004 recession line, and the elevation points representing the bluff elevation superimposed.

Figure 18. West Ohio low shoreline with the associated reach number. Black lines represent shore-normal transects; orange and red lines represent 1 km reaches and reach number; green line represents the 2004 recession line position; and the red points are the adjusted points used to determine recession line elevation.



To define the soil classification, the soil polygon shape-files (Figure 19) for each of the two West Ohio counties were brought into ArcMap, and the dominant soil classification for each 1 km reach was determined. Each 1 km reach was classified either as glacio-lacustrine, till or beach sand, or limestone and was combined with the elevation data to give a bluff height, recession rate, and percentage of coarse material provided to the littoral system.

Figure 19. USDA Soil Classification polygons with 1 km reaches. Each polygon has a 2- to 4-digit classification code indicating the dominant soil type.



Pennsylvania

No stratigraphic cross sections were available for the Pennsylvania shore. Therefore, the stratigraphy has been based on reports by Knuth (2001) and Carter (1977), aerial photography, and personal observations.

In a report prepared for the Great Lakes Commission on the Pennsylvania shore, Kunth (2001) calculated the amount of sediment supplied from bluff erosion in 14 segments using stratigraphy, sediment characteristics, and late twentieth century recession rates. The recession values were calculated at the State of Pennsylvania's recession control points, located at approximately 1 km intervals along the coast, and covered the period 1982–1998. These control points are not at the same locations as the 1 km reaches used in this present study.

Table 8 compares sediment input calculated by Knuth (2001) and Carter (1977) with the results of this present study for the 1874–1938 period.

Table 8. Comparison of bluff sediment volumes along the Pennsylvania shore.

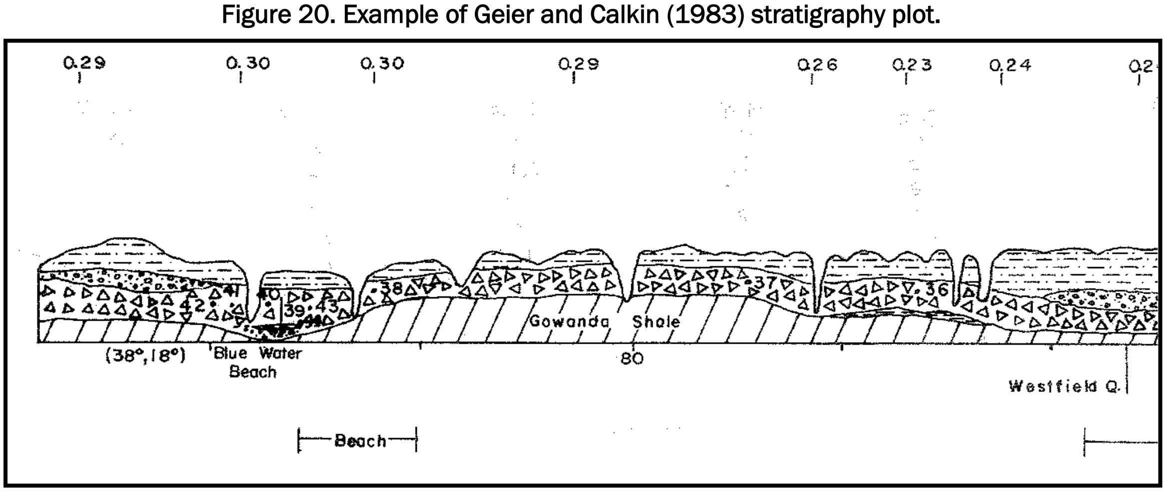
	Knuth (2001) Table 6 1982–1988	Carter (1977) 1870s–1970s	This Present Study, 1874–1938
Conneaut to Presque Isle			
Sand/gravel (m^3/year)	58,640	29,600	38,280
Silt/clay (m^3/year)	148,650		181,075
Erie to PA/NY border			
Sand/gravel (m^3/year)	26,510	58,860	75,075
Silt/clay (m^3/year)	85,410		219,620

From Erie, PA, to the Pennsylvania/New York border, this present study calculated almost four times the volume of coarse sediment that Knuth (2001) reported. The main reason for the increase is the recession rate for the 1874–1938 period used in this study was two to four times the rate Knuth used in his calculations.

New York

Geier and Calkin (1983) published a detailed bluff stratigraphy for the New York coast, which is reproduced in Appendix A. This stratigraphy was plotted on 35 × 42 in. paper, and the location of each 1 km reach along the shoreline was determined using creeks and other prominent geomorphic features (Figure 20). In ArcMap, distances were measured with the measurement tool. Then the same distances were scaled on the paper plot using a Gerber Variable Scale.

Figure 20. Example of Geier and Calkin (1983) stratigraphy plot.



Computation of bluff volumes

The procedure to calculate bluff sediment supply included the following steps:

1. Reaches of 1 km in length developed by Stewart (1999) as a recession rate database for Buffalo District serve as the framework for calculating recession data in this study. These reaches are available in digital form with node locations in latitude-longitude coordinates (NAD83).
2. Using the USACE Corpscon software, convert nodes to UTM Zone 17 coordinates.
3. Import the table into Esri ArcMap software and plot the reach points.
4. Using the Buffer tool in ArcMap, create a 1 km buffer around each reach point.
5. Using the Dissolve tool in ArcMap, remove overlap from cells.
6. From aerial imagery, coarsely trace the approximate bluff/recession line of the lake.
7. Using the Overlay and Split tools, match the traced recession line with the 1 km reaches and split the shoreline into individual reaches. From this, measure an effective length exposed to erosion.
8. Based on the various sources of geomorphic data cited, measure the thickness of strata at each location: shale, till, lacustrine/silt, sand, and limestone.
9. Enter the strata thickness measurements into an Excel data table.
10. Enter a sediment factor representing the proportion of the bluff material that becomes littoral sediment. These factors were approximations and could be refined in the future based on laboratory or field tests of bluff materials.

    a. Shale: Varies from 0.3 to 0.5
    b. Till: Varies

        i. 0.2 (Toledo-Conneaut)
        ii. Variable depending on measurements from Knuth (2001) (Conneaut-Presque Isle)
        iii. 0.25 (Presque Isle-Buffalo)

    c. Lacustrine silts and clays: 0.1
    d. Sand and gravel: 0.95
    e. Limestone: 0.0

11. Overlay transects computed by DSAS with the 1 km reach lines to determine in which 1 km reach each transect falls.
12. For each 1 km reach, average the recession rate from the appropriate transects.
13. To determine predicted future sediment volumes, draw polylines representing areas where the shoreline has been armored. This is determined from high-resolution aerial imagery and oblique imagery acquired by the USACE (http://greatlakes.usace.army.mil/). These data are exportable as a .csv file, which is then pulled into ArcMap and set up with hyperlinking to ease overlay and viewing of imagery. Overlay the hardened shoreline polylines with the cross-shore transects. For each transect that intersects a hardened shoreline, set the future recession rate to zero.
14. Estimate the contribution of each strata for each reach using the Volume Contribution Formula, Equation 2:

$$\text{Sed-vol} = \text{Strata\_ht} \times \text{Factor} \times \text{Recession\_rate} \times \text{Effective\_reach\_length} \quad (2)$$

15. Overlay the 1 km transects with the littoral cells to determine sediment inputs to each cell. Where a 1 km reach falls into two or more littoral cells, determine the percentage of the reach that falls within each and apply the appropriate ratio of material to each cell.
16. Sum up the littoral volumes for each littoral cell.

Patsch and Griggs (2006) described a similar procedure to calculate sediment volumes supplied by bluffs along the Pacific coast of California. As they pointed out, bluff calculations have a high degree of uncertainty because of the high spatial variability of sediment content and episodic nature of cliff or bluff failure.

The predicted Future sediment budget is based on the bluff recession rates from the Recent time frame, but volumes are adjusted to reflect the lengths of shoreline that are now armored (these are treated as zero sediment input). It also incorporates bypassing at harbors based on dredging data.

Computed sediment volumes

Tables 9 and 10 list the sediment volumes per reach of the Lake Erie shoreline for Pre-Armoring and Mid-Century time frames and Recent and Future time frames, respectively.

Table 9. Bluff recession volumes for the Pre-Armoring (1860s to 1930s) and Mid-Century (1930s to 1970s) time frames (all units in cubic meters/year).

Reach	Pre-Armoring Total Bluff Volume	Pre-Armoring Total Coarse Volume	Pre-Armoring Total Fine Volume	Pre-Armoring Coarse Loss to deep	Pre-Armoring Coarse Continue to Littoral System	Mid-Century Total Bluff Volume	Mid-Century Coarse Bluff Volume	Mid-Century Fine Bluff Volume	Mid-Century Coarse Loss to deep	Mid-Century Coarse Continue to Littoral System
Toledo-Cooley Canal	68900	6900	62000	1400	5500	58800	5900	52900	1200	4700
Cooley Canal Harbor	1600	100	1500	100	0	3500	400	3100	100	300
Cooley Canal-Locust Point Nodal Point	39900	4000	35900	800	3200	25600	2500	23100	500	2000
Locust Point Nodal Point-Port Clinton	33100	3300	29800	700	2600	19600	2000	17600	400	1600
Port Clinton Harbor	0	0	0	0	0	3200	300	2900	100	200
Port Clinton-Catawba Island Nodal Point	5400	800	4600	200	600	17100	2100	15000	400	1700
Catawba Island Nodal Point-West Harbor	1100	100	1000	0	100	2100	400	1700	100	300
West Harbor-Marblehead Nodal Point	5400	500	4900	100	400	7900	900	7000	200	700
Marblehead Nodal Point-Sandusky	2100	200	1900	0	200	2700	400	2300	100	300
Sandusky-Huron	7000	3500	3500	700	2800	11300	10300	1000	2100	8200
Huron Harbor	0	0	0	0	0	0	0	0	0	0
Huron-Vermilion	41600	6600	35000	1300	5300	30400	5400	25000	1100	4300
Vermilion Harbor	0	0	0	0	0	0	0	0	0	0
Vermilion Harbor Fillet	1000	300	700	100	200	600	100	500	0	100
Vermilion-Beaver Park Marina	22700	4600	18100	900	3700	10000	2700	7300	600	2100
Beaver Park Marina	4600	500	4100	100	400	2200	300	1900	100	200
Beaver Park Marina-Lorain	22600	4400	18200	900	3500	4900	1000	3900	200	800
Lorain Harbor West	500	100	400	0	100	100	0	100	0	0

Reach	Pre-Armoring Total Bluff Volume	Pre-Armoring Total Coarse Volume	Pre-Armoring Total Fine Volume	Pre-Armoring Coarse Loss to deep	Pre-Armoring Coarse Continue to Littoral System	Mid-Century Total Bluff Volume	Mid-Century Coarse Bluff Volume	Mid-Century Fine Bluff Volume	Mid-Century Coarse Loss to deep	Mid-Century Coarse Continue to Littoral System
Lorain Harbor East	0	0	0	0	0	0	0	0	0	0
Lorain-Domonkas Library	11300	2300	9000	400	1900	5000	1000	4000	200	800
Domonkas Library	500	100	400	0	100	100	0	100	0	0
Domonkas Library-Avon Lake	5200	1100	4100	200	900	1700	400	1300	100	300
Avon Lake	2000	500	1500	100	400	200	0	200	0	0
Avon Lake-Avon Lake Nodal Point	3300	900	2400	200	700	1700	500	1200	100	400
Avon Lake Nodal Point-Rocky River	50400	17400	33000	3500	13900	18200	5900	12300	1200	4700
Rocky River Harbor	0	0	0	0	0	0	0	0	0	0
Rocky River-Cleveland	33100	9700	23400	2000	7700	17400	5100	12300	1000	4100
Cleveland Harbor Fillet	0	0	0	0	0	0	0	0	0	0
Cleveland Harbor	0	0	0	0	0	0	0	0	0	0
Cleveland-White City Park	15500	5700	9800	1100	4600	11000	4500	6500	900	3600
White City Park	0	0	0	0	0	0	0	0	0	0
White City Park-Cleveland Lakefront St Park	1300	300	1000	100	200	1400	300	1100	100	200
Cleveland Lakefront. St Park	1100	200	900	0	200	600	100	500	0	100
Cleveland Lakefront St Park-Eastlake PP	58100	11600	46500	2300	9300	41000	8300	32700	1700	6600
Eastlake Power Plant Fillet	7100	1600	5500	300	1300	2600	600	2000	100	500
Eastlake Power Plant	2100	400	1700	100	300	500	100	400	0	100
Eastlake Power Plant-Mentor Harbor	53700	14200	39500	2800	11400	30500	8500	22000	1700	6800
Mentor Harbor Fillet	0	0	0	0	0	0	0	0	0	0

Reach	Pre-Armoring Total Bluff Volume	Pre-Armoring Total Coarse Volume	Pre-Armoring Total Fine Volume	Pre-Armoring Coarse Loss to deep	Pre-Armoring Coarse Continue to Littoral System	Mid-Century Total Bluff Volume	Mid-Century Coarse Bluff Volume	Mid-Century Fine Bluff Volume	Mid-Century Coarse Loss to deep	Mid-Century Coarse Continue to Littoral System
Mentor Harbor-Fairport	28500	6000	22500	1200	4800	55200	11500	43700	2300	9200
Fairport Harbor Fillet	500	100	400	0	100	0	0	0	0	0
Fairport Harbor	8600	1700	6900	300	1400	1300	300	1000	100	200
Fairport-North Perry	124200	33600	90600	6700	26900	172300	50300	122000	10100	40200
North Perry Marina	2300	900	1400	200	700	2800	1100	1700	200	900
North Perry-Geneva-on-the-Lake	24300	12900	11400	2600	10300	9200	5000	4200	1000	4000
Geneva-on-the-Lake Fillet	600	100	500	0	100	900	200	700	0	200
Geneva-on-the-Lake	200	100	100	0	100	300	100	200	0	100
Geneva-on-the-Lake-Ashtabula	66300	13400	52900	2700	10700	42500	8600	33900	1700	6900
Ashtabula Harbor Fillet	0	0	0	0	0	0	0	0	0	0
Ashtabula Harbor	0	0	0	0	0	0	0	0	0	0
Ashtabula-Conneaut	140300	42400	97900	8500	33900	97200	31900	65300	6400	25500
Conneaut Harbor Fillet	400	100	300	0	100	300	100	200	0	100
Conneaut Harbor	1700	300	1400	100	200	200	0	200	0	0
Conneaut-Presque Isle	228900	47800	181100	9600	38200	261800	52400	209400	10500	41900
Presque Isle	0	0	0	0	0	198200	198200	0	39600	158600
Erie East Fillet	0	0	0	0	0	0	0	0	0	0
Erie-Shades Beach	51300	13800	37500	2800	11000	31100	8400	22700	1700	6700
Shades Beach	1500	400	1100	100	300	1500	400	1100	100	300
Shades Beach-Crittenden Point	162000	40800	121200	8100	32700	125700	31700	94000	6300	25400
Crittenden Point-North East Marina	69600	17500	52100	3500	14000	80700	20200	60500	4000	16200
North East Marina Fillet	900	200	700	0	200	900	200	700	0	200

Reach	Pre-Armoring Total Bluff Volume	Pre-Armoring Total Coarse Volume	Pre-Armoring Total Fine Volume	Pre-Armoring Coarse Loss to deep	Pre-Armoring Coarse Continue to Littoral System	Mid-Century Total Bluff Volume	Mid-Century Coarse Bluff Volume	Mid-Century Fine Bluff Volume	Mid-Century Coarse Loss to deep	Mid-Century Coarse Continue to Littoral System
North East Marina	700	200	500	0	200	700	200	500	100	100
North East Marina-Twentymile Creek Point	3800	900	2900	200	700	3200	800	2400	200	600
Twentymile Creek Point-Barcelona	84200	20800	63400	4100	16700	20800	5100	15700	1000	4100
Barcelona Fillet	0	0	0	0	0	400	100	300	0	100
Barcelona Harbor	700	200	500	100	100	100	0	100	0	0
Barcelona-Van Buren Point	116400	31600	84800	6300	25300	33300	8600	24700	1700	6900
Van Buren Point-Dunkirk	4400	1100	3300	200	900	2800	600	2200	100	500
Dunkirk Outer Basin	500	100	400	0	100	400	100	300	0	100
Dunkirk Harbor	0	0	0	0	0	0	0	0	0	0
Dunkirk-Fletcher Point	20500	6000	14500	1200	4800	7700	2300	5400	500	1800
Fletcher Point-Silver Creek	20000	5800	14200	1100	4700	3400	1000	2400	200	800
Silver Creek	6700	2000	4700	400	1600	1000	300	700	100	200
Cattaraugus Fillet	0	0	0	0	0	0	0	0	0	0
Cattaraugus	0	0	0	0	0	0	0	0	0	0
Cattauragus Sturgeon Point	45800	29700	16100	6000	23700	10500	6000	4500	1200	4800
Sturgeon Point Fillet	800	300	500	0	300	300	100	200	0	100
Sturgeon Point	2800	1000	1800	200	800	1000	400	600	100	300
Sturgeon Point-Buffalo	60100	17400	42700	3500	13900	26000	7600	18400	1500	6100

Table 10. Bluff recession volumes for the Recent (1970s to 2000s) and Future time frames (all units in cubic meters/year).

Reach	Recent Total Bluff Volume	Recent Coarse Bluff Volume	Recent Fine Bluff Volume	Recent Coarse Loss to deep	Recent Coarse Continue to Littoral System	Future Total Bluff Volume	Future Coarse Bluff Volume	Future Fine Bluff Volume	Future Coarse Loss to deep	Future Coarse Continue to Littoral System
Toledo-Cooley Canal	12500	1300	11200	300	1000	1800	200	1600	0	200
Cooley Canal Harbor	300	0	300	0	0	0	0	0	0	0
Cooley Canal-Locust Point Nodal Point	17800	1800	16000	400	1400	5200	500	4700	100	400
Locust Point Nodal Point-Port Clinton	8400	800	7600	100	700	7100	700	6400	100	600
Port Clinton Harbor	0	0	0	0	0	0	0	0	0	0
Port Clinton-Catawba Island Nodal Point	3200	300	2900	100	200	2000	100	1900	0	100
Catawba Island Nodal Point-West Harbor	1200	200	1000	0	200	200	0	200	0	0
West Harbor-Marblehead Nodal Point	3800	600	3200	100	500	2000	400	1600	100	300
Marblehead Nodal Point-Sandusky	400	0	400	0	0	100	0	100	0	0
Sandusky-Huron	14300	13500	800	2700	10800	14200	13500	700	2700	10800
Huron Harbor	0	0	0	0	0	0	0	0	0	0
Huron-Vermilion	19200	3200	16000	600	2600	11800	2000	9800	400	1600
Vermilion Harbor	0	0	0	0	0	0	0	0	0	0
Vermilion Harbor Fillet	400	100	300	0	100	400	100	300	0	100
Vermilion-Beaver Park Marina	10100	2700	7400	500	2200	3900	1000	2900	200	800
Beaver Park Marina	800	100	700	0	100	800	100	700	0	100
Beaver Park Marina-Lorain	1100	200	900	0	200	800	200	600	100	100
Lorain Harbor West	0	0	0	0	0	0	0	0	0	0
Lorain Harbor East	0	0	0	0	0	0	0	0	0	0

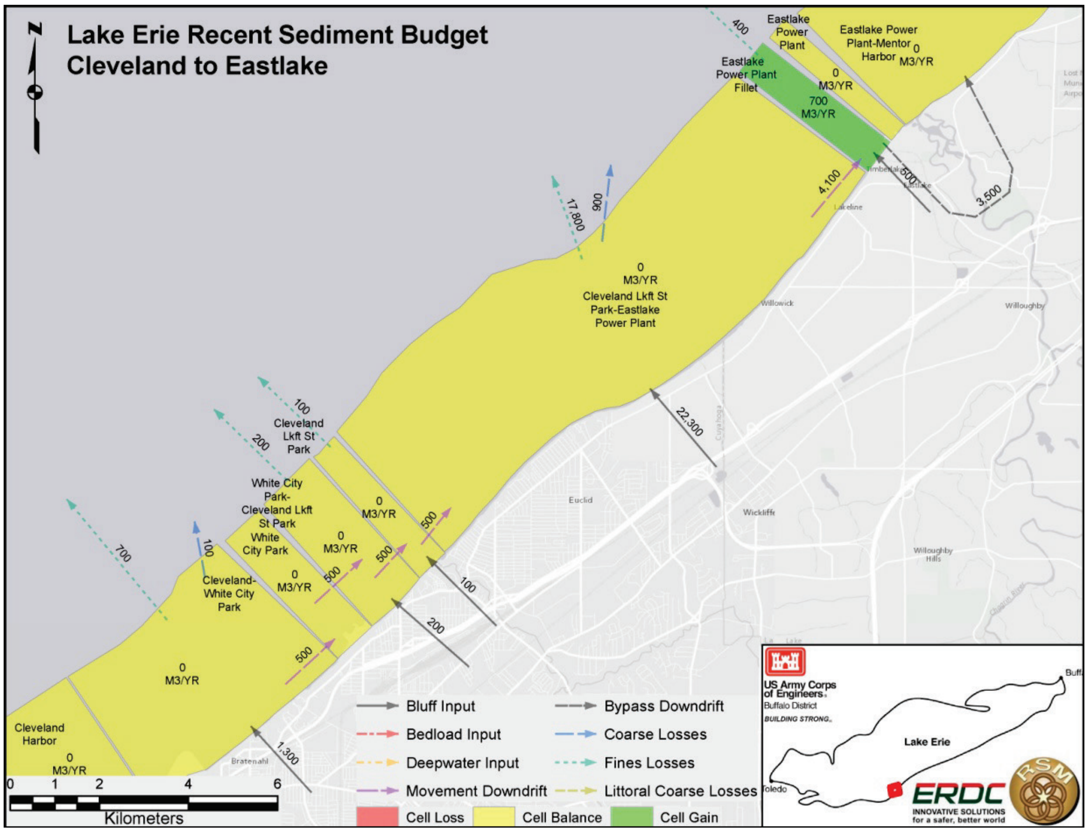
Reach	Recent Total Bluff Volume	Recent Coarse Bluff Volume	Recent Fine Bluff Volume	Recent Coarse Loss to deep	Recent Coarse Continue to Littoral System	Future Total Bluff Volume	Future Coarse Bluff Volume	Future Fine Bluff Volume	Future Coarse Loss to deep	Future Coarse Continue to Littoral System
Lorain-Domonkas Library	1300	300	1000	100	200	500	100	400	0	100
Domonkas Library	100	0	100	0	0	0	0	0	0	0
Domonkas Library-Avon Lake	2200	500	1700	100	400	900	200	700	0	200
Avon Lake	300	100	200	0	100	0	0	0	0	0
Avon Lake-Avon Lake Nodal Point	1100	300	800	100	200	300	100	200	0	100
Avon Lake Nodal Point-Rocky River	14200	4600	9600	900	3700	8100	2500	5600	500	2000
Rocky River Harbor	0	0	0	0	0	0	0	0	0	0
Rocky River-Cleveland	9000	2600	6400	500	2100	7500	2200	5300	400	1800
Cleveland Harbor Fillet	0	0	0	0	0	0	0	0	0	0
Cleveland Harbor	0	0	0	0	0	0	0	0	0	0
Cleveland-White City Park	1300	600	700	100	500	300	100	200	0	100
White City Park	0	0	0	0	0	0	0	0	0	0
White City Park-Cleveland Lakefront St Park	200	0	200	0	0	100	0	100	0	0
Cleveland Lakefront St Park	100	0	100	0	0	100	0	100	0	0
Cleveland Lakefront St Park-Eastlake PP	22300	4500	17800	900	3600	9800	2000	7800	400	1600
Eastlake Power Plant Fillet	500	100	400	0	100	500	100	400	0	100
Eastlake Power Plant	0	0	0	0	0	0	0	0	0	0
Eastlake Power Plant-Mentor Harbor	30300	7700	22600	1600	6100	18900	4800	14100	1000	3800
Mentor Harbor Fillet	1900	1800	100	400	1400	1800	1700	100	400	1300
Mentor Harbor-Fairport	12300	2800	9500	600	2200	10600	2500	8100	500	2000
Fairport Harbor Fillet	0	0	0	0	0	0	0	0	0	0

Reach	Recent Total Bluff Volume	Recent Coarse Bluff Volume	Recent Fine Bluff Volume	Recent Coarse Loss to deep	Recent Coarse Continue to Littoral System	Future Total Bluff Volume	Future Coarse Bluff Volume	Future Fine Bluff Volume	Future Coarse Loss to deep	Future Coarse Continue to Littoral System
Fairport Harbor	0	0	0	0	0	0	0	0	0	0
Fairport-North Perry	155700	43500	112200	8700	34800	115000	33300	81700	6700	26600
North Perry Marina	1000	400	600	100	300	500	200	300	0	200
North Perry-Geneva-on-the-Lake	20600	12100	8500	2400	9700	16200	9900	6300	2000	7900
Geneva-on-the-Lake Fillet	900	200	700	100	100	300	100	200	0	100
Geneva-on-the-Lake	300	100	200	0	100	100	0	100	0	0
Geneva-on-the-Lake-Ashtabula	40200	8100	32100	1600	6500	26200	5200	21000	1000	4200
Ashtabula Harbor Fillet	0	0	0	0	0	0	0	0	0	0
Ashtabula Harbor	0	0	0	0	0	0	0	0	0	0
Ashtabula-Conneaut	190200	63100	127100	12600	50500	158500	50500	108000	10100	40400
Conneaut Harbor Fillet	0	0	0	0	0	0	0	0	0	0
Conneaut Harbor	400	0	400	0	0	400	0	400	0	0
Conneaut-Presque Isle	171300	37900	133400	7600	30300	159600	35700	123900	7100	28600
Presque Isle	26600	26600	0	4000	22600	26600	26600	0	4000	22600
Erie East Fillet	0	0	0	0	0	0	0	0	0	0
Erie-Shades Beach	31000	8300	22700	1700	6600	29600	7900	21700	1600	6300
Shades Beach	1500	400	1100	100	300	1300	300	1000	0	300
Shades Beach-Crittenden Point	98900	24900	74000	5000	19900	97000	24500	72500	4900	19600
Crittenden Point-North East Marina	59200	14900	44300	3000	11900	47600	11900	35700	2400	9500
North East Marina Fillet	700	200	500	0	200	400	100	300	0	100
North East Marina	500	100	400	0	100	300	100	200	0	100
North East Marina-Twentymile Creek Point	2400	600	1800	100	500	600	200	400	0	200

Reach	Recent Total Bluff Volume	Recent Coarse Bluff Volume	Recent Fine Bluff Volume	Recent Coarse Loss to deep	Recent Coarse Continue to Littoral System	Future Total Bluff Volume	Future Coarse Bluff Volume	Future Fine Bluff Volume	Future Coarse Loss to deep	Future Coarse Continue to Littoral System
Twentymile Creek Point-Barcelona	20500	5000	15500	1000	4000	17300	4300	13000	900	3400
Barcelona Fillet	100	0	100	0	0	100	0	100	0	0
Barcelona Harbor	0	0	0	0	0	0	0	0	0	0
Barcelona-Van Buren Point	33500	9100	24400	1800	7300	31900	8700	23200	1700	7000
Van Buren Point-Dunkirk	1400	300	1100	100	200	900	200	700	100	100
Dunkirk Outer Basin	200	0	200	0	0	200	0	200	0	0
Dunkirk Harbor	0	0	0	0	0	0	0	0	0	0
Dunkirk-Fletcher Point	15000	4400	10600	900	3500	14700	4300	10400	900	3400
Fletcher Point-Silver Creek	4300	1300	3000	300	1000	3700	1100	2600	200	900
Silver Creek	1000	300	700	100	200	1000	300	700	100	200
Cattaraugus Fillet	0	0	0	0	0	0	0	0	0	0
Cattaraugus	0	0	0	0	0	0	0	0	0	0
Cattauragus Sturgeon Point	7500	3800	3700	700	3100	6500	3300	3200	700	2600
Sturgeon Point Fillet	100	0	100	0	0	100	0	100	0	0
Sturgeon Point	300	100	200	0	100	300	100	200	0	100
Sturgeon Point-Buffalo	12300	3500	8800	700	2800	8100	2400	5700	500	1900

The bluff recession data displayed in Table 9 and Table 10 were brought into SBAS to determine total Longshore Sediment Transport (LST). Based on flux directions, the coarse fraction of the bluff material was summed as necessary to determine the magnitude of each flux. The LST quantities were also compared with the computed harbor sedimentation rates to refine the positioning and magnitude of sediment flux. Figure 21 presents an example of the completed sediment budget from Cleveland to Fairport Harbor, OH. The entire sediment budget for Lake Erie is presented in Appendix B.

Figure 21. Completed sediment budget, Cleveland to Eastlake, during the Recent time frame.



The net littoral volumes are listed in Table 11 and Table 12 for Pre-Armoring and Mid-Century time frames, and Recent and Future time frames, respectively. “Net Coarse Volume In” represents the sum of any coarse fraction from updrift, from bluff erosion, and from bed load into a littoral cell. “Coarse Loss at end of Cell” represents any material lost to deep water at the end of a littoral cell. The “Net Coarse Volume to Downdrift” represents the quantity of material transported into the downdrift littoral cell. The “Net Volume Retained” represents the ΔV term in Equation 1.

Table 11. Net littoral cell volumes for the Pre-Armoring (1860s to 1930s) and Mid-Century (1930s to 1970s) time frames (all units in cubic meters/year).

	Pre-Armoring				Mid-Century			
Reach	Net Coarse Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Toledo-Cooley Canal	8800	0	8800	0	7000	0	7000	0
Cooley Canal Harbor	3300	0	3300	0	2300	0	2300	0
Cooley Canal-Locust Point Nodal Point	3200	0	3200	0	2000	0	2000	0
Locust Point Nodal Point-Port Clinton	2700	0	2700	0	1600	0	1600	0
Port Clinton Harbor	3200	600	0	2600	3500	700	0	2800
Port Clinton-Catawba Island Nodal Point	600	0	600	0	1700	0	1700	0
Catawba Island Nodal Point-West Harbor	100	0	100	0	300	0	300	0
West Harbor	500	0	0	500	1000	0	0	1000
West Harbor-Marblehead Nodal Point	400	0	400	0	700	0	700	0
Marblehead Nodal Point-Sandusky	200	0	200	0	300	0	0	300
Sandusky-Huron	4100	4100	0	0	8200	8200	0	0
Huron Harbor	5000	1300	1300	2500	4000	0	0	4000
Huron-Vermilion	5300	0	5300	0	4300	0	4300	0
Vermilion Harbor	1200	0	0	1200	1000	0	0	1000
Vermilion Harbor Fillet	1700	0	900	800	1200	0	700	500
Vermilion-Beaver Park Marina	3700	0	3700	0	2100	0	2100	0
Beaver Park Marina	2600	0	2600	0	1200	0	1400	-200
Beaver Park Marina-Lorain	6100	0	6100	0	2200	0	2200	0
Lorain Harbor West	6200	0	0	6200	2200	0	0	2200
Lorain Harbor East	4000	0	0	4000	1100	0	0	1100
Lorain - Domonkas Library	4000	0	4000	0	1100	0	1100	0
Domonkas Library	2100	0	2100	0	300	0	300	0

	Pre-Armoring				Mid-Century			
Reach	Net Coarse Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Domonkas Library-Avon Lake	2000	0	2000	0	300	0	300	0
Avon Lake	1100	0	1100	0	400	0	0	400
Avon Lake - Avon Lake Nodal Point	700	0	700	0	400	0	400	0
Avon Lake Nodal Point - Rocky River	13900	0	13900	0	4700	0	4700	0
Rocky River Harbor	13900	4600	9300	0	4700	0	0	4700
Rocky River-Cleveland	17000	0	17000	0	4100	0	4100	0
Cleveland Harbor Fillet	17000	0	0	17000	4100	2100	0	2000
Cleveland Harbor	17000	8500	0	8500	0	0	0	0
Cleveland-White City Park	4600	0	4600	0	3600	0	3600	0
White City Park	4600	0	4600	0	3600	0	2600	1000
White City Park-Cleveland Lakefront St Park	4800	0	4800	0	2800	0	2800	0
Cleveland Lkft St Park	5000	0	5000	0	2900	0	1900	1000
Cleveland Lkft St Park-Eastlake PP	14300	0	14300	0	8500	0	8500	0
Eastlake Power Plant Fillet	15600	0	15600	0	9000	0	8000	1000
Eastlake Power Plant	15900	0	15900	0	100	0	100	0
Eastlake Power Plant-Mentor Harbor	27300	0	27300	0	14900	0	14900	0
Mentor Harbor Fillet	27300	0	27300	0	14900	0	13900	1000
Mentor Harbor-Fairport	32100	0	32100	0	23100	0	23100	0
Fairport Harbor Fillet	32200	0	3600	28600	23100	0	4800	18300
Fairport Harbor	5000	0	0	5000	5000	0	0	5000
Fairport-North Perry	26900	0	26900	0	40200	0	40200	0
North Perry Marina	27600	0	27600	0	41100	0	41100	0
North Perry-Geneva-on-the-Lake	37900	0	37900	0	45100	0	45100	0

Reach	Pre-Armoring				Mid-Century			
	Net Coarse Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Geneva-on-the-Lake Fillet	38000	0	38000	0	45300	0	45300	0
Geneva-on-the-Lake	38100	0	38100	0	45400	0	45400	0
Geneva-on-the-Lake-Ashtabula	48800	0	48800	0	52300	0	52300	0
Ashtabula Harbor Fillet	48800	6400	34400	8000	52300	24300	10000	18000
Ashtabula Harbor	34300	6500	6500	21400	10000	0	0	10000
Ashtabula-Conneaut	40400	0	40400	0	25500	0	25500	0
Conneaut Harbor Fillet	40500	10200	30300	0	25600	0	15600	10000
Conneaut Harbor	30500	10300	10200	10000	15600	0	0	15600
Conneaut-Presque Isle	48500	0	48500	0	41900	0	41900	0
Presque Isle	48500	48500	0	0	200500	0	221000	-20500
Gull Point	0	0	0	0	221000	156100	0	64900
Erie East Fillet	0	0	0	0	0	0	0	0
Erie - Shades Beach	11000	0	11000	0	6700	0	6700	0
Shades Beach	11300	0	11300	0	7000	0	7000	0
Shades Beach-Crittenden Point	44000	22000	22000	0	32300	16200	16200	0
Crittenden Point-North East Marina	36000	0	36000	0	32400	0	32400	0
North East Marina Fillet	36200	0	36200	0	32500	0	32500	0
North East Marina	36300	0	36300	0	32700	0	32700	0
North East Marina-Twentymile Creek Point	37100	18500	18500	0	33300	16700	16600	0
Twentymile Creek Point-Barcelona	35200	0	35200	0	20700	0	20700	0
Barcelona Fillet	35200	17600	17600	0	20800	10400	5200	5200
Barcelona Harbor	17700	0	17700	0	5200	0	5300	-100
Barcelona-Van Buren Point	43000	21500	21500	0	12200	6100	6100	0

Reach	Pre-Armoring				Mid-Century			
	Net Coarse Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Van Buren Point-Dunkirk	22400	11200	11200	0	6600	3300	3300	0
Dunkirk Outer Basin	11300	8500	1300	1500	3400	2500	1400	-500
Dunkirk Harbor	1300	0	0	1300	5400	0	0	5400
Dunkirk-Fletcher Point	4800	500	4300	0	1800	200	1600	0
Fletcher Point-Silver Creek	9000	900	8100	0	2400	200	2200	0
Silver Creek	9700	0	9700	0	2400	0	2400	0
Cattaraugus Fillet	9700	0	9700	0	2400	0	2400	0
Cattaraugus	12400	0	12400	0	5100	0	5100	0
Cattaraugus Shoal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cattaraugus Scour	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cattauragus Sturgeon Point	36100	0	36100	0	9900	0	9900	0
Sturgeon Point Fillet	36400	9100	27300	0	10000	2500	7500	0
Sturgeon Point	28100	0	28100	0	7800	0	7800	0
Sturgeon Point-Buffalo	42000	0	42000	0	13900	0	13900	0

Table 12. Net littoral cell volumes for the Recent (1970s to 2000s) and Future time frames (all units in cubic meters/year).

Reach	Recent				Future			
	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Toledo-Cooley Canal	1000	0	1000	0	200	0	200	0
Cooley Canal Harbor	1400	0	0	1400	400	0	0	400
Cooley Canal-Locust Point Nodal Point	1400	0	1400	0	400	0	400	0
Locust Point Nodal Point-Port Clinton	700	0	700	0	600	0	600	0
Port Clinton Harbor	900	1,200	0	-300	700	1,200	0	-500
Port Clinton-Catawba Island Nodal Point	200	0	200	0	100	0	100	0
Catawba Island Nodal Point-West Harbor	200	0	200	0	0	0	0	0
West Harbor	600	0	0	600	300	0	0	300
West Harbor-Marblehead Nodal Point	500	0	500	0	300	0	300	0
Marblehead Nodal Point-Sandusky	0	0	0	0	0	0	0	0
Sandusky-Huron	10800	10800	0	0	10800	10800	0	0
Huron Harbor	2300	0	0	2300	1400	0	0	1400
Huron-Vermilion	2600	0	2600	0	1600	0	1600	0
Vermilion Harbor	800	0	0	800	500	0	0	500
Vermilion Harbor Fillet	900	0	500	400	700	0	300	400
Vermilion-Beaver Park Marina	2200	0	2200	0	800	0	800	0
Beaver Park Marina	1500	500	500	1000	300	100	100	100
Beaver Park Marina-Lorain	700	0	700	0	200	0	200	0
Lorain Harbor West	700	0	0	700	200	0	0	200
Lorain Harbor East	600	0	0	600	100	0	0	100
Lorain - Domonkas Library	600	0	600	0	100	0	100	0
Domonkas Library	400	0	400	0	200	0	0	200

Reach	Recent				Future			
	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Domonkas Library-Avon Lake	400	0	400	0	200	0	200	0
Avon Lake	300	0	0	300	100	0	0	100
Avon Lake - Avon Lake Nodal Point	300	0	300	0	100	0	100	0
Avon Lake Nodal Point - Rocky River	3700	0	3700	0	2000	0	2000	0
Rocky River Harbor	3600	0	0	3600	2000	0	0	2000
Rocky River-Cleveland	2100	0	2100	0	1800	0	1800	0
Cleveland Harbor Fillet	2100	1100	0	1100	1800	900	0	900
Cleveland Harbor	0	0	0	0	0	0	0	0
Cleveland-White City Park	500	0	500	0	100	0	100	0
White City Park	500	0	500	0	100	0	100	0
White City Park-Cleveland Lkft St Park	500	0	500	0	100	0	100	0
Cleveland Lakefront St Park	500	0	500	0	200	0	200	0
Cleveland Lakefront St Park-Eastlake PP	4100	0	4100	0	1800	0	1800	0
Eastlake Power Plant Fillet	4300	0	3500	700	1900	0	1400	500
Eastlake Power Plant	0	0	0	0	0	0	0	0
Eastlake Power Plant-Mentor Harbor	9600	0	9600	0	5200	0	5200	0
Mentor Harbor Fillet	11000	0	10300	700	6500	0	6000	500
Mentor Harbor-Fairport	12500	0	12500	0	8000	0	8000	0
Fairport Harbor Fillet	12500	0	4600	7900	8000	0	4600	3400
Fairport Harbor	4600	0	0	4600	4600	0	0	4600
Fairport-North Perry	34800	0	34800	0	26600	0	26600	0
North Perry Marina	35100	0	35100	0	26800	0	26800	0
North Perry-Geneva-on-the-Lake	44800	0	44800	0	34700	0	34700	0

Reach	Recent				Future			
	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Geneva-on-the-Lake Fillet	44900	0	39900	5000	34800	8700	21100	5000
Geneva-on-the-Lake	40000	0	39500	500	21100	0	20600	500
Geneva-on-the-Lake-Ashtabula	46000	0	46000	0	24800	0	24800	0
Ashtabula Harbor Fillet	46000	30000	10000	6000	24800	12300	7500	5000
Ashtabula Harbor	10000	0	0	10000	7500	0	0	7500
Ashtabula-Conneaut	50500	0	50500	0	40400	0	40400	0
Conneaut Harbor Fillet	50500	10500	32000	8000	40400	10400	25000	5000
Conneaut Harbor	32000	0	0	32000	25000	0	0	25000
Conneaut-Presque Isle	30300	0	30300	0	28600	0	28600	0
Presque Isle	52900	0	52900	0	51200	0	51200	0
Gull Point	52900	39000	0	13900	51200	39000	0	12200
Erie East Fillet	0	0	0	0	0	0	0	0
Erie-Shades Beach	6600	0	6600	0	6300	0	6300	0
Shades Beach	6900	0	6900	0	6600	0	5000	1700
Shades Beach-Crittenden Point	26900	13400	13400	0	24500	12300	12300	0
Crittenden Point-North East Marina	25300	0	25300	0	21800	0	21800	0
North East Marina Fillet	25500	0	12400	13100	21900	0	12400	9500
North East Marina	100	0	0	100	100	0	0	100
North East Marina-Twentymile Creek Point	12900	6400	6500	0	12600	6300	6300	0
Twentymile Creek Point-Barcelona	10500	0	10500	0	9700	0	9700	0
Barcelona Fillet	10500	5400	1600	3500	9700	5900	800	3000
Barcelona Harbor	1600	0	-800	2400	800	0	-400	1200
Barcelona-Van Buren Point	6500	3200	3300	0	6500	3300	3300	0

Reach	Recent				Future			
	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained	Net Volume In	Coarse Loss at End of Cell	Net Coarse Volume to Downdrift	Net Volume Retained
Van Buren Point-Dunkirk	3500	1700	1700	0	3400	1700	1700	0
Dunkirk Outer Basin	1800	1400	1400	-1000	1800	1300	1400	-1000
Dunkirk Harbor	3400	0	0	3400	3400	0	0	3400
Dunkirk-Fletcher Point	3500	300	3200	0	3400	300	3100	0
Fletcher Point-Silver Creek	4200	400	3800	0	4000	400	3600	0
Silver Creek	4000	0	4000	0	3800	0	3800	0
Cattaraugus Fillet	4000	0	900	3100	3800	0	1900	1900
Cattaraugus	3500	0	3500	0	4600	0	4600	0
Cattaraugus Shoal	0	4400	13100	-17500	0	900	2600	-3500
Cattaraugus Scour	17700	2000	9700	6000	8000	1500	4500	2000
Cattauragus Sturgeon Point	12700	0	12700	0	7100	0	7100	0
Sturgeon Point Fillet	12700	0	12700	0	7100	0	7100	0
Sturgeon Point	5200	0	5200	0	2200	0	2200	0
Sturgeon Point-Buffalo	15600	0	15600	0	9100	0	9100	0

9 Harbor Comparisons

Computing changes in sediment volume at harbor structures provides a means to confirm the computed bluff erosion volumes. Sediment volume change computations have been completed at 12 of the Buffalo District Harbors (Section 5). The historic sediment budget developed for Presque Isle as part of the 1980 Phase II General Design Memorandum (USACE 1984) was used for comparison as well. Appendix C contains a complete set of figures for the harbors analyzed in this present study.

Port Clinton Harbor

Port Clinton Harbor structures consist of East (375 m long) and West (205 m long) Piers. Construction began in 1872, and the earliest data used for sediment computation date to 1881.

To model the budget at Port Clinton Harbor, only a harbor cell was used (cell 5). The harbor has been relatively stable over the years, accreting slowly over much of the time since construction. The cell at Port Clinton is modeled to have sediment coming in from both the east and the west, with some sediments accumulating within the cell while most is lost offshore.

The harbor analysis at Port Clinton Harbor indicated a depositional rate of 400 m^3/year at the harbor in the Pre-Armoring time frame (200 m^3/year both east and west of the harbor). Due to the limited data available to model Port Clinton Harbor, the harbor analysis rates likely underpredict sediment changes in the Pre-Armoring and Mid-Century time frames. The bluff analysis during the Pre-Armoring time frame indicates 3,200 m^3/year moving into Port Clinton. The cell was modeled with a loss of 1,200 m^3/year to offshore, leaving a total accretion rate of 2,000 m^3/year.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 1,200 m^3/year (600 m^3/year both east and west of the harbor). As with the Pre-Armoring time frame, limited data restrict the coverage of the harbor analysis, underpredicting sediment gains. The bluff analysis measured a total of 3,500 m^3/year of sediment moving into the Port Clinton cell. The cell was modeled with a loss of 1,200 m^3/year to offshore, leaving a total accretion rate of 2,300 m^3/year.

In the Recent time frame, the harbor analysis measured net erosion at a rate of 1,500 m^3/year at Port Clinton. The erosion rate was measured as -1,100 m^3/year east of the harbor and -400 m^3/year west of the harbor. Due to shoreline hardening, sediment inputs into the cell decreased dramatically to a total of 900 m^3/year. A loss of 1,200 m^3/year is estimated to deep water, leaving a net erosion rate of -300 m^3/year.

In the Future time frame, the incoming sediment load will decrease to 700 m^3/year with a continued loss of 1,200 m^3/year to offshore, resulting in a net erosion rate of -500 m^3/year.

Table 13 gives predicted and measured sediment flux values at Port Clinton Harbor.

Table 13. Predicted and measured volumetric change at Port Clinton Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
East		200		600		-1,100	
West		200		600		-400	
Total	2,000	400	2,300	1,200	-300	-1,500	-500
	Total Difference	2,200	Total Difference	1,100	Total Difference	1,200	1,000
		550%		92%		-80%	-67%

The SBAS cells for Port Clinton from the Pre-Armoring through the Future time frames are presented in Figures 22 through 25.

Figure 22. Port Clinton Harbor Pre-Armoring sediment budget.

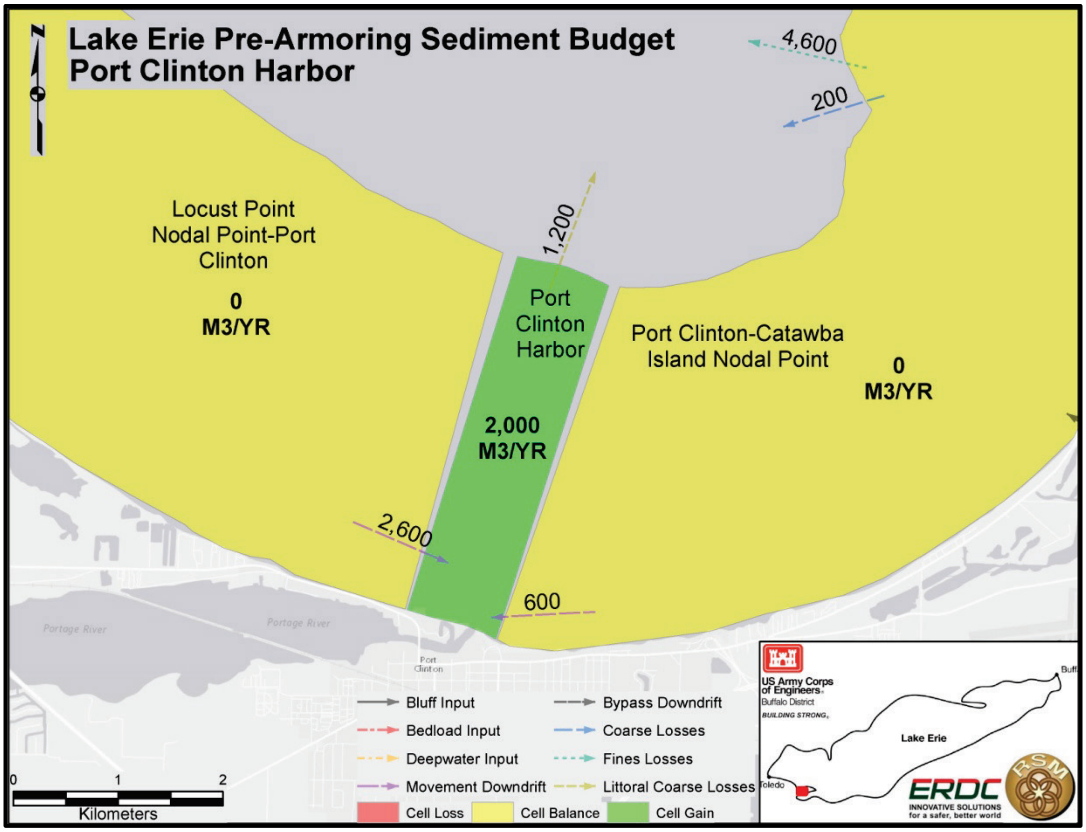


Figure 23. Port Clinton Harbor Mid-Century sediment budget.

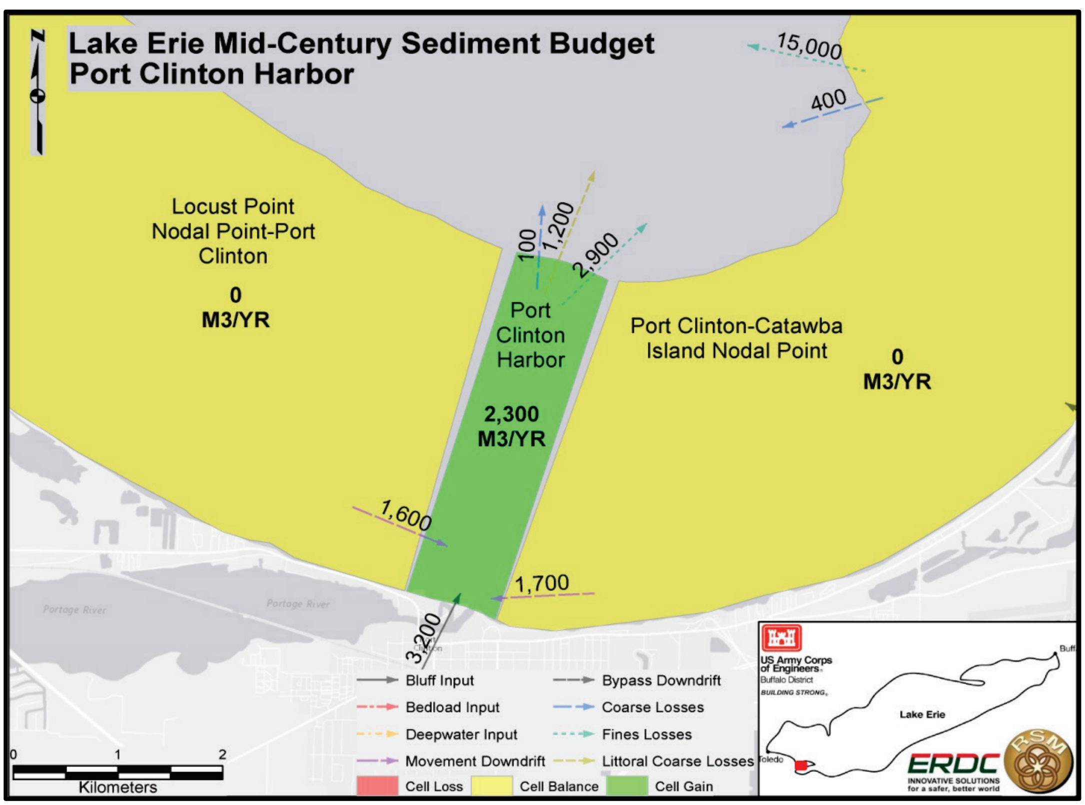


Figure 24. Port Clinton Harbor Recent sediment budget.

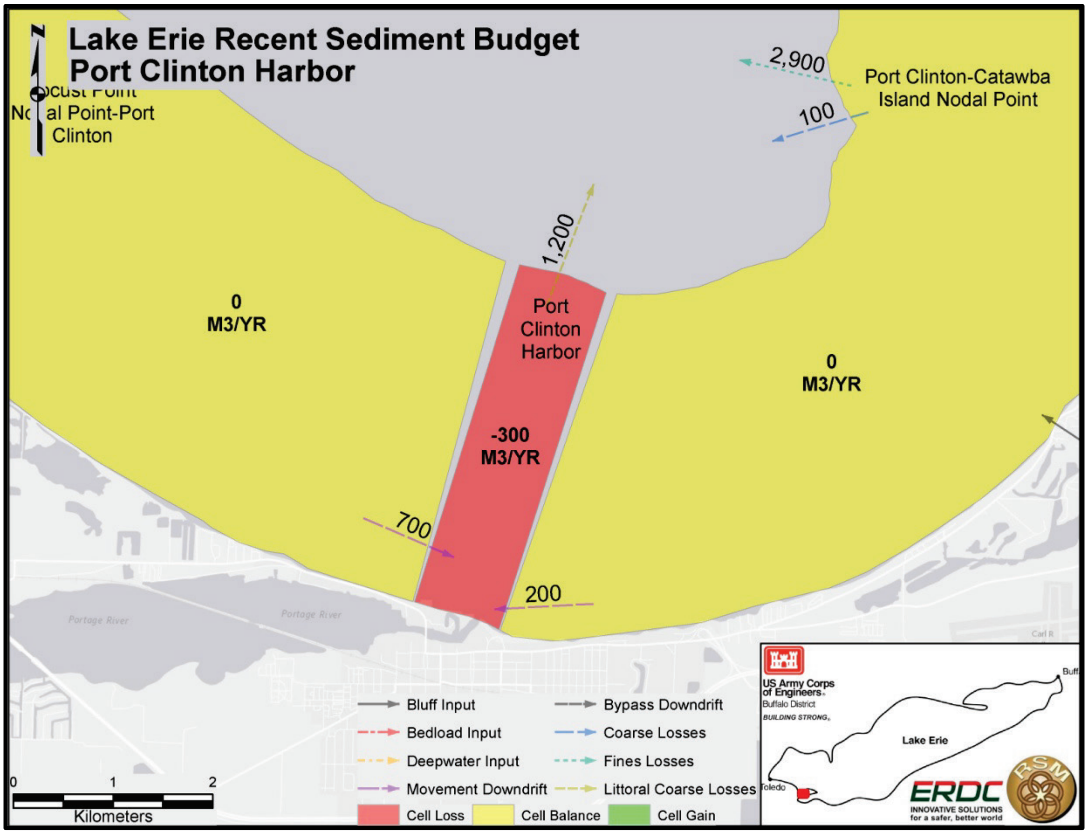
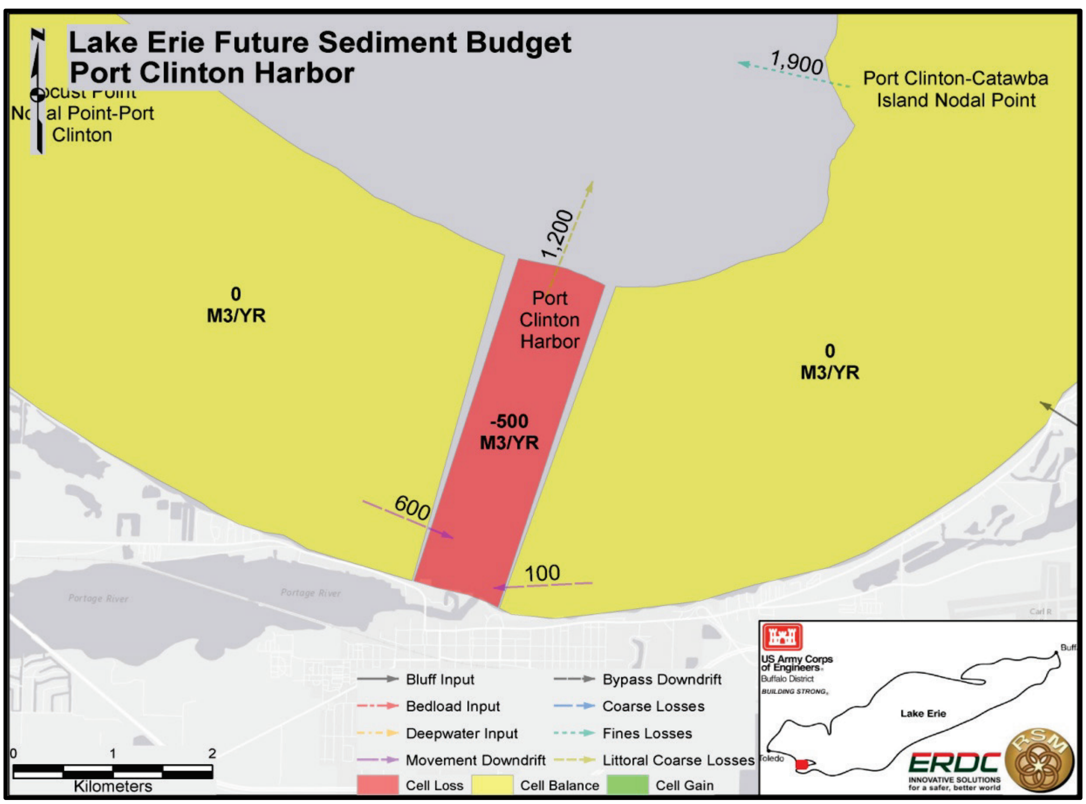


Figure 25. Port Clinton Harbor Future sediment budget.



West Harbor

West Harbor structures consist of 410 m long North and South breakwaters. Construction of structures began in 1981, and the earliest data used for sediment computation date to 1958. The Mid-Century time frame is considered the pre-construction period.

To model the budget at West Harbor, only a harbor cell was used (cell 8). Prior to construction, minor erosion was dominant east of the harbor and minor deposition was occurring to the west.

There were no harbor data available to measure conditions at the harbor in the Pre-Armoring time frame. The bluff analysis measured a total of 500 m^3/year depositing at West Harbor.

The harbor analysis of the pre-construction conditions (Mid-Century time frame) at West Harbor indicated a depositional rate of 500 m^3/year west of West Harbor and an erosion rate of 100 m^3/year to the east, producing a net rate of change of 400 m^3/year. The bluff analysis measured a total of 1,000 m^3/year of sediment depositing at West Harbor. In the Recent time frame, the harbor analysis measured an accretion rate of 900 m^3/year at West Harbor (800 m^3/year west of the harbor and 100 m^3/year to the east). The bluff analysis measured a total of 700 m^3/year of sediment moving through the littoral system.

In the Future time frame, the incoming sediment load is predicted to decrease to 300 m^3/year.

Table 14 gives predicted and measured sediment flux values at West Harbor.

Table 14. Predicted and measured volumetric change at West Harbor (all units in cubic meters/year).

	Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
East		-100		100	
West		500		800	
Total	1,000	400	700	900	300
	Total Difference	600	Total Difference	-200	-600
		150%		-22%	-67%

The SBAS cells for West Harbor from the Mid-Century through the Future time frames are presented in Figures 26 through 28.

Figure 26. West Harbor Mid-Century sediment budget.

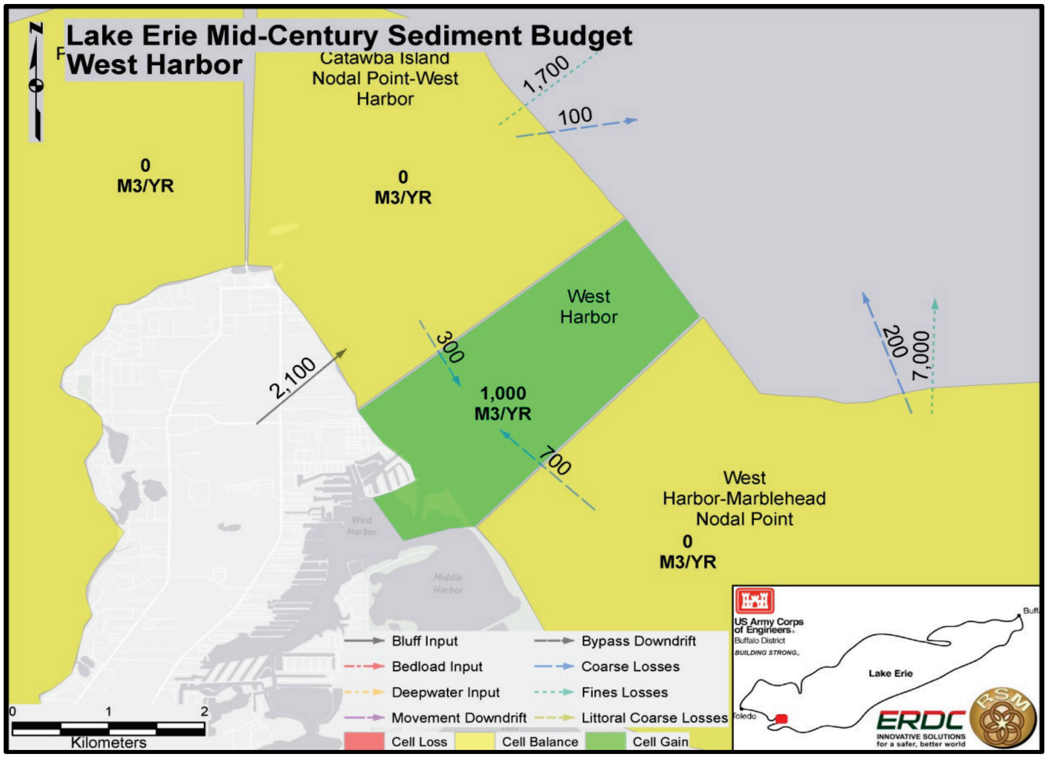


Figure 27. West Harbor Recent sediment budget.

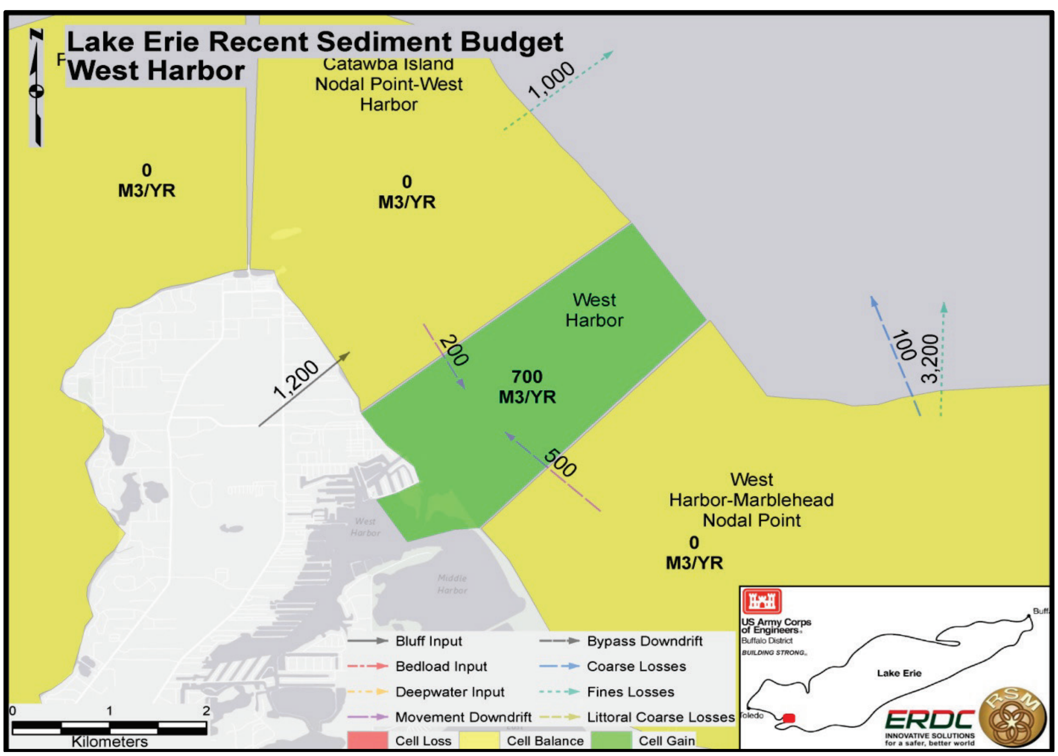
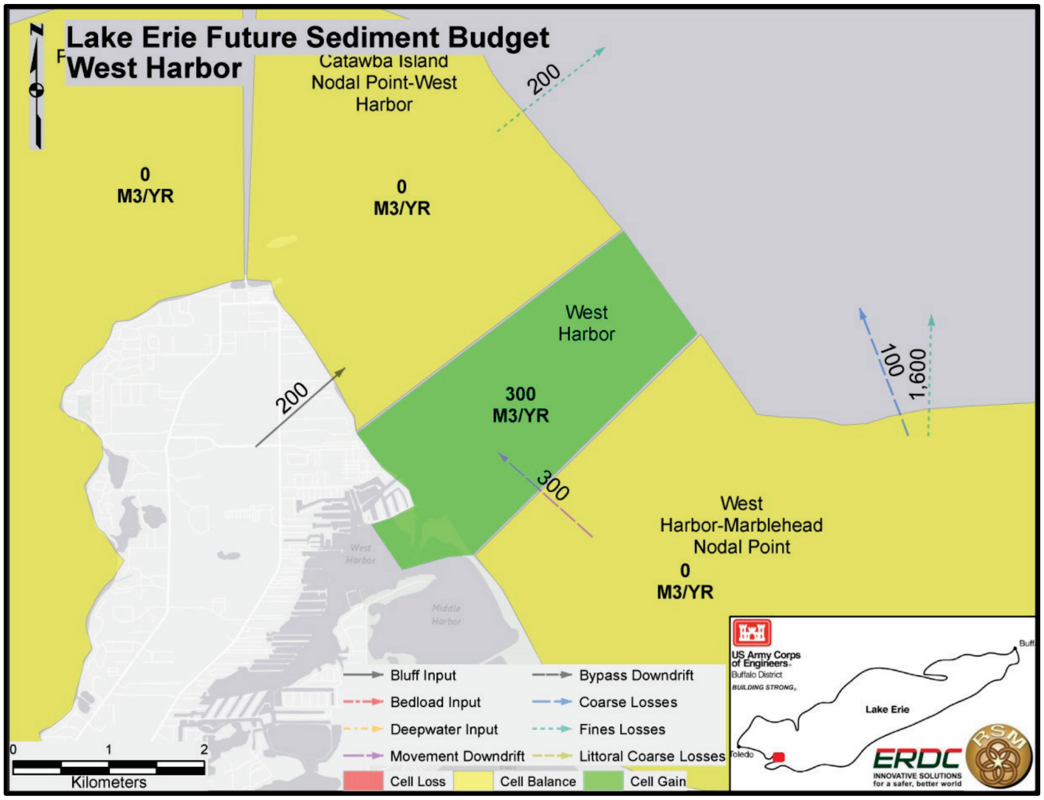


Figure 28. West Harbor Future sediment budget.



Huron Harbor

Huron Harbor structures consist of East (440 m long) and West (1075 m long) Breakwaters and a Confined Disposal Facility (CDF) operated by the Buffalo District. Construction of structures began in 1827 with installation of the East and West Piers. The east jetty was added in 1909, and the CDF was completed in 1974. The earliest data used for sediment computation date to 1877.

To model the budget at Huron Harbor, only a harbor cell was used (cell 12). Sediment movement in this area follows a predominantly east-to-west direction. With construction of the piers, erosion became the dominant process to the west of Huron Harbor, and the harbor change analysis measured an erosion rate of -1,900 m^3/year. The region to the east of the harbor remained relatively stable, with a measured change of -100 m^3/year. As the piers at Huron were constructed during this time frame, erosion to the west of the harbor was dominant while transport across the harbor decreased dramatically. The bluff analysis resulted in an input measurement of 5,000 m^3/year into Huron Harbor. It is estimated that 1,300 m^3/year was lost from Huron Harbor to the down-drift cell and

1,300 m^3/year was lost to offshore during the Pre-Armoring time frame. This results in a net change at Huron Harbor of 2,500 m^3/year. The difference between the estimated volumes from the bluff analysis and the measured volume change at the harbor during the Pre-Armoring time frame is likely a function of increased dredging activity at the harbor.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 4,600 m^3/year (1,300 m^3/year to the west of the harbor and 3,300 m^3/year to the east). By this time frame, the erosion to the west of the harbor had stabilized, resulting in accretion due to short-term reversals in the LST direction. The east jetty was also constructed during this time frame, leading to deposition within the east basin and to the east of the harbor. The bluff analysis measured a total of 4,000 m^3/year of sediment accreting in the Huron Harbor cell coming from the east.

In the Recent time frame, the harbor analysis measured an accretion rate of 4,600 m^3/year (2,100 m^3/year to the west of the harbor and 2,500 m^3/year to the east). Shoreline hardening caused the volume of material measured from the bluffs coming into the eastern section of Huron Harbor to decrease to 2,300 m^3/year. During this time frame, the CDF at Huron Harbor was completed, further protecting the western section of the harbor from erosion.

In the Future time frame, the incoming sediment load will decrease to 1,400 m^3/year from the east due to shoreline hardening.

Table 15 gives predicted and measured sediment flux values at Huron Harbor.

Table 15. Predicted and measured volumetric change at Huron Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
East		-100		3,300		-200	
West		-1,900		1,300		2,100	
Total	2,500	-2,000	4,000	4,600	2,300	1,900	
	Total Difference	4,500	Total Difference	-600	Total Difference	-400	1,400
		-225%		-13%		21%	-26%

The SBAS cells for Huron from the Pre-Armoring through the Future time frames are presented in Figures 29 through 32.

Figure 29. Huron Harbor Pre-Armoring sediment budget.

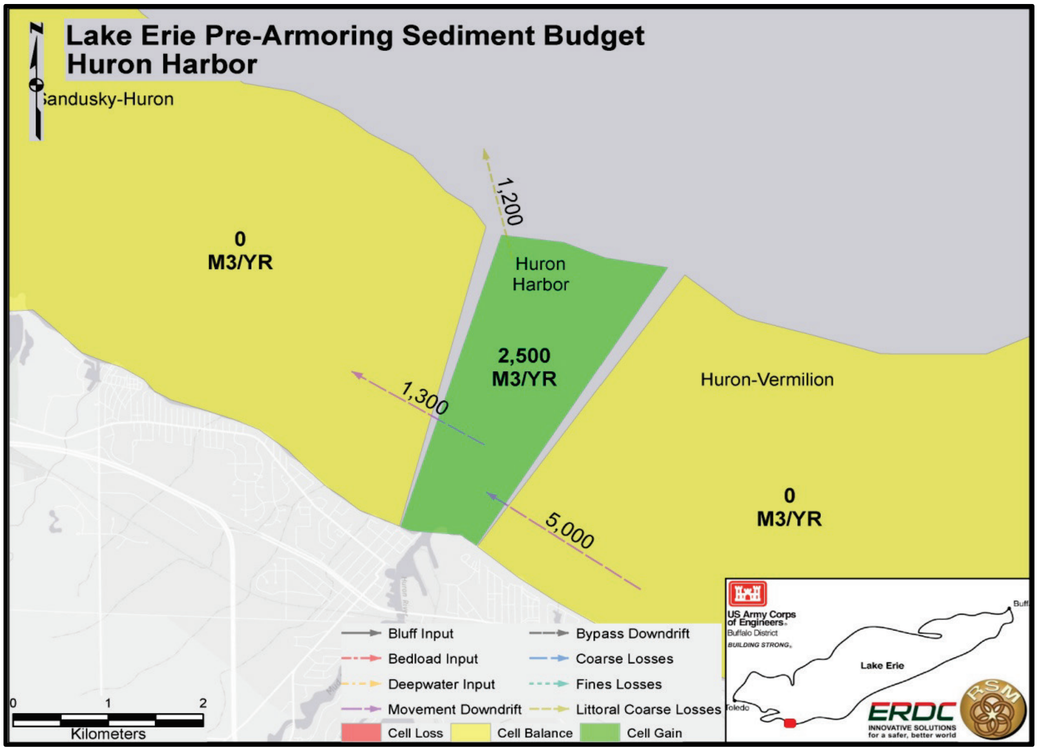


Figure 30. Huron Harbor Mid-Century sediment budget.

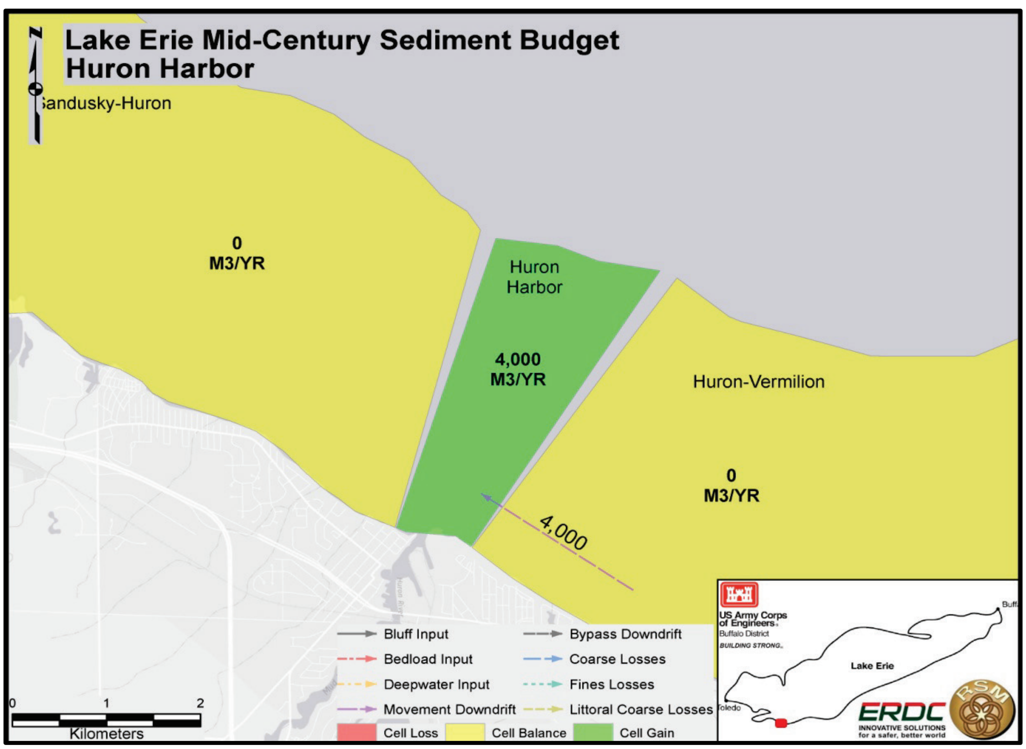


Figure 31. Huron Harbor Recent sediment budget.

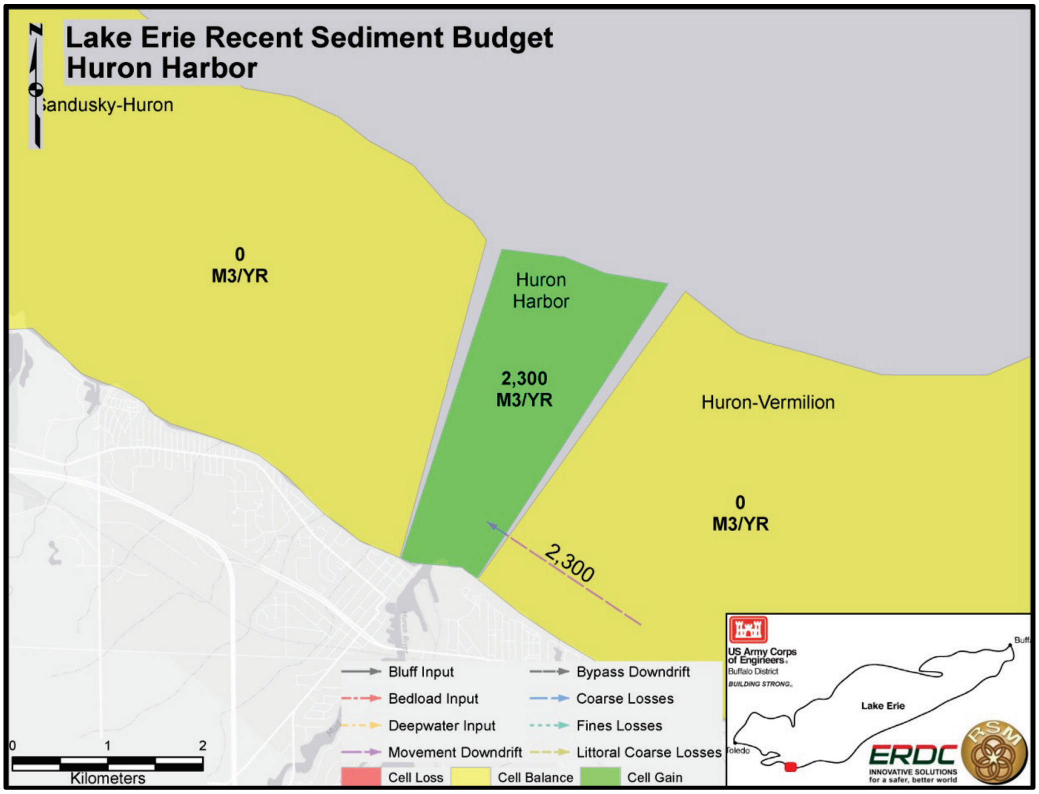
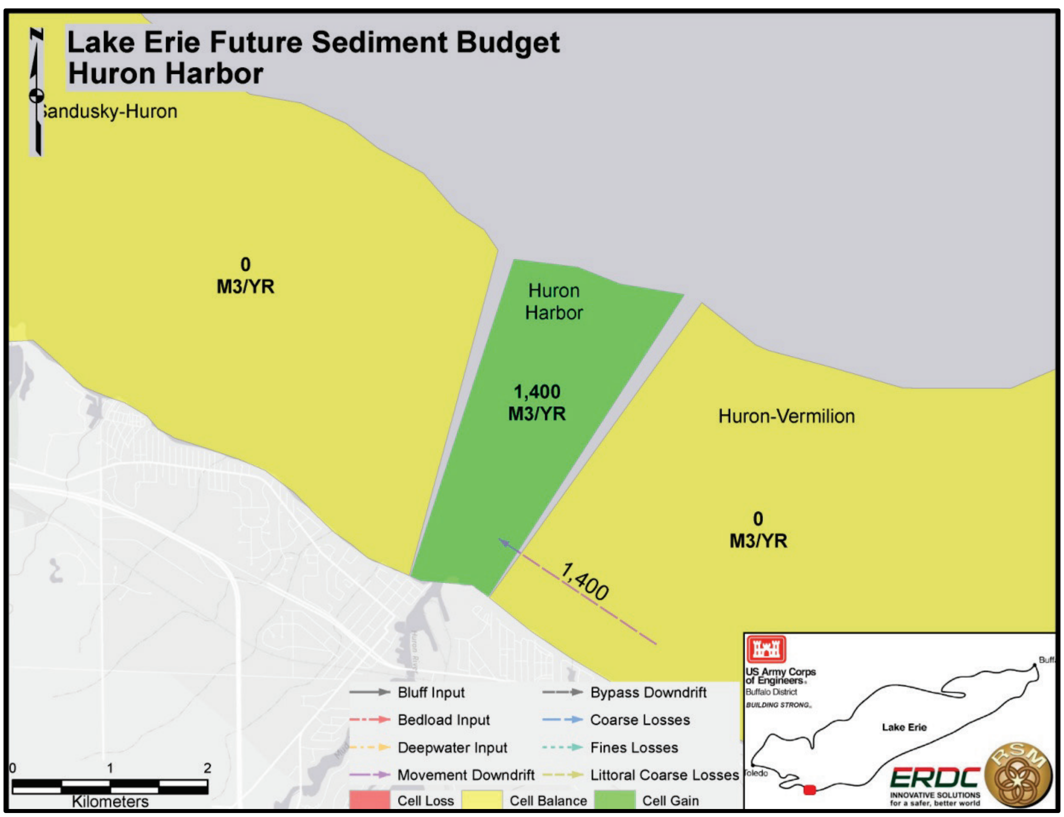


Figure 32. Huron Harbor Future sediment budget.



Vermilion Harbor, Beaver Park Marina, and Lorain Harbor, OH

Historically, the dominant direction of LST in this reach has been modeled from east to west, going from the Avon Lake Nodal Point east of Lorain and continuing west to Huron Harbor and farther to the west along the Cedar Point Peninsula. Analysis of aerial imagery, sedimentation rates at the harbors, and littoral volumes contributed to the system from bluff erosion has raised questions as to the dominant direction of LST.

A review of historical imagery indicates that the shoreline at Vermilion has been remarkably stable for both the Mid-Century and Recent time frames. Beaver Park Marina has been relatively stable on the east side while the west side underwent erosion in the Mid-Century time frame before accreting after construction of additional jetty in the Recent time frame. At Lorain, sediment accretes the east and west sides of the harbor.

Historic shorelines are overlain on the 2006 ortho-imagery for Vermilion Harbor, Beaver Park Marina, and Loraine Harbor in Figure 33, Figure 34, and Figure 35, respectively. Volumetric changes at Vermilion and Lorain Harbors are listed in Table 16, and bluff erosion volumes are listed in Table 17.

Table 16. Volumetric change rates at Lorain and Vermilion Harbors, OH (all units in cubic meters/year).

	Timeframe		
Harbor-Region	Pre-Armoring	Mid-Century	Recent
Lorain-East	2,600	6,000	-200
Lorain-West	6,800	6,600	4,300
Vermilion-East	600	400	900
Vermilion-West	900	900	300

Table 17. LST Volumes from bluff erosion (all units in cubic meters/year).

	Coarse Contribution to Littoral System			
Littoral Cell	Pre-Armoring	Mid-Century	Recent	Future
To Lorain from East	4,000	1,100	600	100
Lorain-Beaver Park Marina, OH	3,400	800	200	100
Beaver Park Marina, OH	400	200	100	100
Beaver Park Marina-Vermilion	3,700	2,200	2,200	800
Vermilion Harbor Fillet	200	100	100	100
Total	7,700	3,300	2,600	1,100

Figure 33. Historic shorelines and accretion rates at Vermilion Harbor, OH (inset map shows position along shoreline between Vermilion and Lorain, OH).

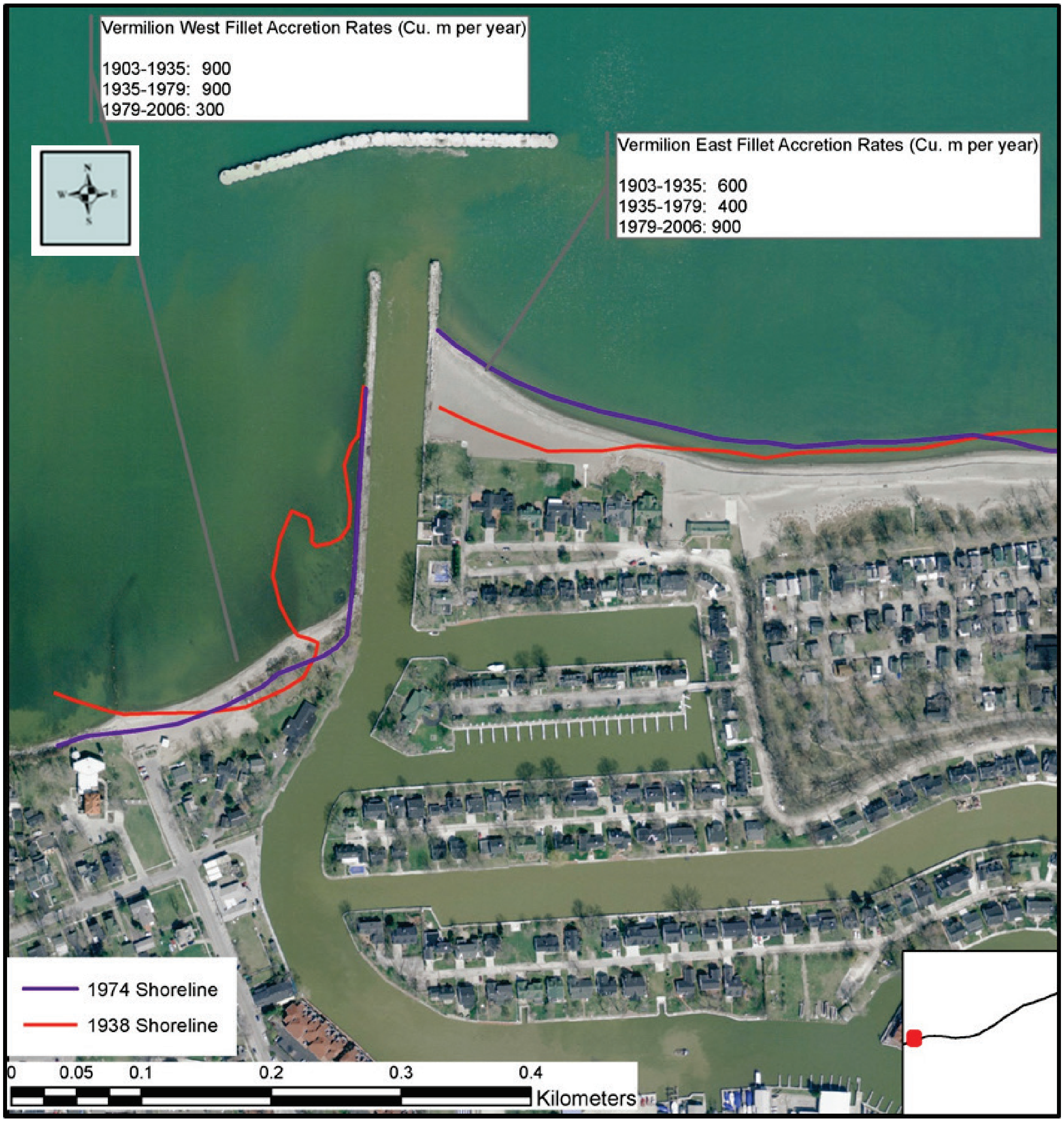


Figure 34. Historic shorelines at Beaver Park Marina, OH (inset map shows position along shoreline between Vermillion and Lorain, OH).

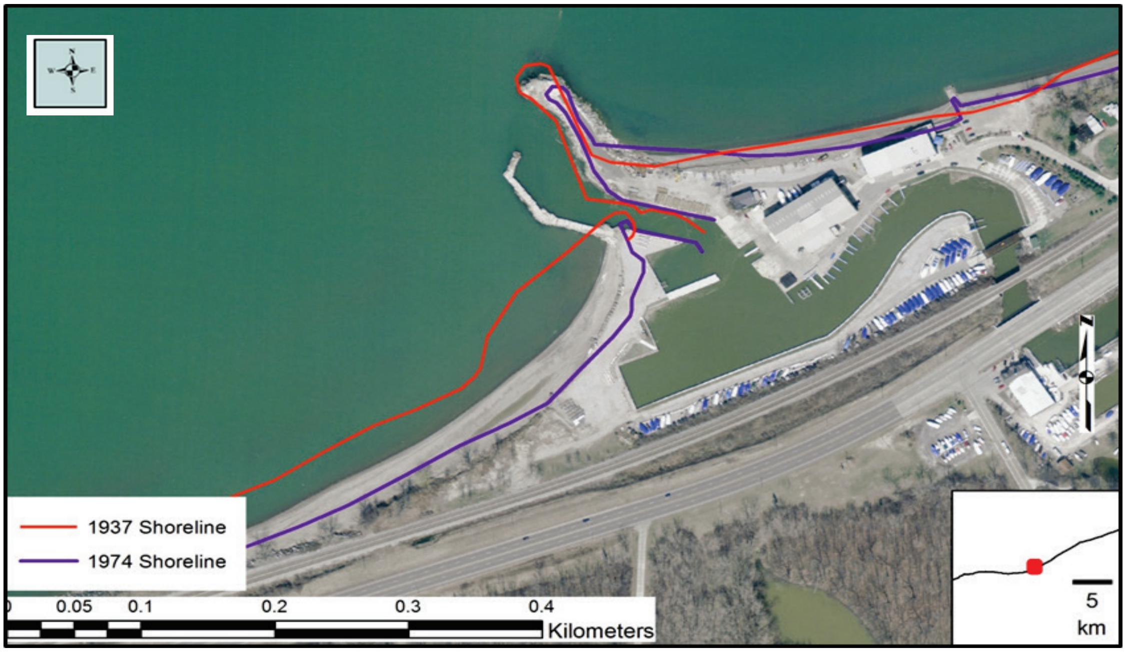
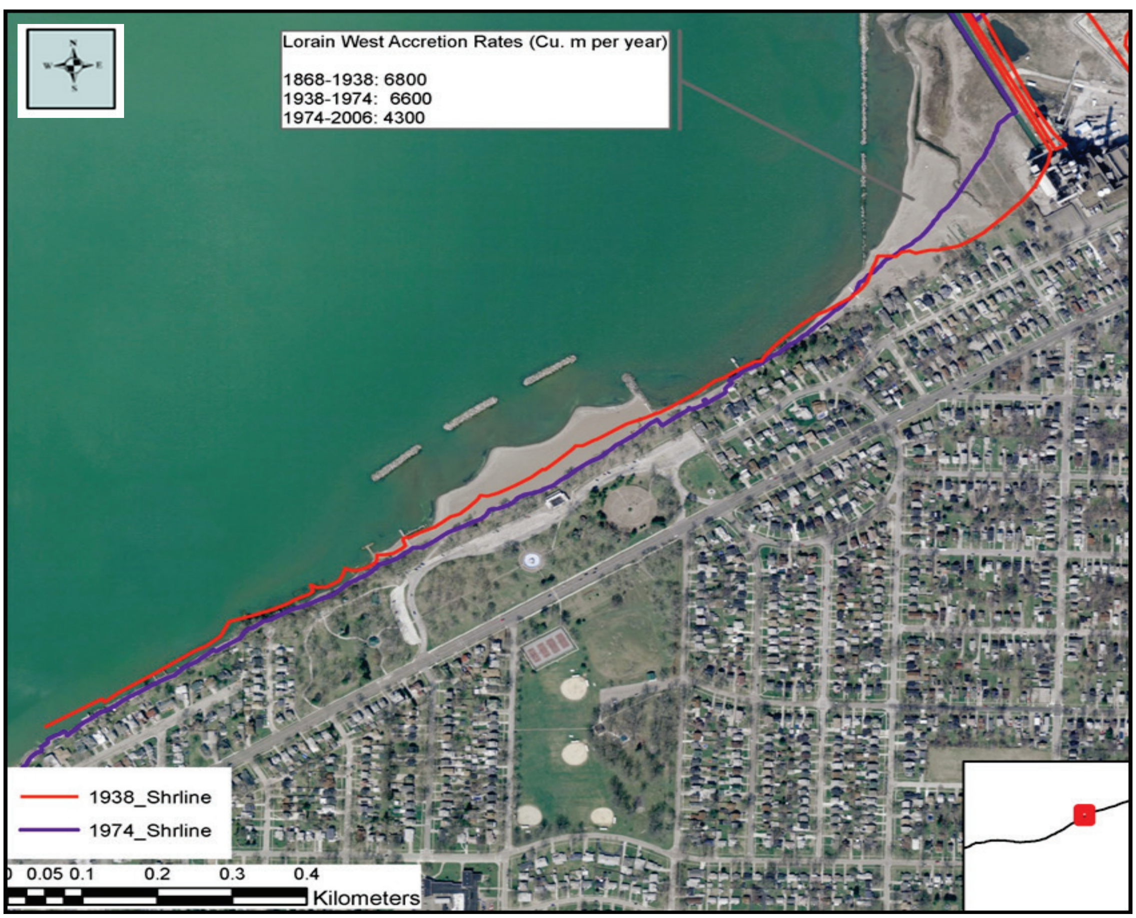


Figure 35. Historic shorelines and accretion rates at the west side of Lorain Harbor, OH (inset map shows position along shoreline between Vermilion and Lorain).



Vermilion Harbor

Vermilion Harbor structures consist of East (140 m long) and West (405 m long) Piers and a Detached Breakwater (263 m long). Construction of structures began in 1837, and the earliest data used for sediment computation date to 1874.

The uncertainty in dominant LST direction complicates budget modeling at Vermilion Harbor. Here, two cells were used: a harbor cell and a fillet cell (cells 14 and 15, respectively). The west side of Vermilion Harbor has remained very stable throughout all three time frames. The harbor analysis measured volumetric change rates in the harbor cell of Vermilion Harbor of 900, 900, and 300 m^3/year for the Pre-Armoring, Mid-Century, and Recent time frames, respectively.

A substantial pocket beach or fillet leads up to the East Pier at Vermilion, but this beach has not increased substantially in volume during the period over which modeling occurred. The harbor analysis measured volumetric change rates in the fillet cell of Vermilion Harbor of 600, 400, and 900 m^3/year for the Pre-Armoring, Mid-Century, and Recent time frames, respectively.

Beaver Park Marina

Beaver Park Marina structures consist of east (180 m long) and west (160 m long) jetties. The east jetty has been in place at least since 1937 while the west jetty was built sometime between 1974 and 2006. A volumetric computation was not carried out at Beaver Park Marina due to a lack of bathymetric data, but visual observation shows that the shoreline along the west jetty was eroding up to the construction of the jetty and has been accreting since while the shoreline along the east jetty has been stable since the Mid-Century time frame. The lack of change along the east jetty as well as the accretion west of the harbor since construction of the west jetty indicates that LST is predominantly west to east.

Lorain Harbor

Lorain Harbor structures consist of East and West piers (East, 615 m long; West, 990 m long), and Outer (665 m long) Breakwaters, and East (708 m long) and West (229 m long) Shorearm Breakwaters. Construction began in 1828, but the earliest data available for sediment computation date to 1865.

Short-term reversals to the LST direction occur in this area, but the magnitude of these reversals has not been quantified. Because of this, determination of sediment fluxes at Lorain Harbor is challenging. To model the budget at Lorain, two cells were used: a west cell and an east cell (cells 19 and 20, respectively).

The west basin has undergone accretion in all three time frames, demonstrating the presence of a west-to-east component of LST along this stretch of shoreline. The measured accretion rate in the west cell has decreased moderately over the course of the three time frames, from 6,800 m^3/year in the Pre-Armoring time frame, to 6,600 m^3/year in the Mid-Century time frame, to 4,300 m^3/year in the Recent time frame. Due to structure construction and creation of a deep-water navigation channel, it is unlikely that sediment was transported across the harbor from the east to the west side.

The east cell underwent accretion for the Pre-Armoring and Mid-Century time frames but had a net loss of material in the Recent time frame. Computation of sediment accumulation in the Recent time frame was impeded by the construction of a confined disposal facility (CDF) and Small Boat Harbor, thus shifting the areas from which volume change was measured. The recent lidar acquisition at Lorain Harbor failed to capture bathymetric data, further limiting data analysis. The harbor analysis measured volumetric change rates in the east cell of Lorain Harbor at 2,600 m^3/year, 6,000 m^3/year, and -200 m^3/year for the Pre-Armoring, Mid-Century, and Recent time frames, respectively. LST from the east for the three time frames was measured to be 4,000 m^3/year, 1,100 m^3/year, and 600 m^3/year, respectively.

Discussion and modeling

To model this reach within SBAS, the LST direction on the east side of Lorain was assumed to be east to west, depositing sediment into the Lorain Harbor east cell. Between Lorain Harbor and Beaver Park Marina, the LST was assumed to be west to east, depositing sediment in the Lorain Harbor west cell. Between Beaver Park Marina and Lorain, the dominant direction of sediment movement is not clear, so sediment transport was modeled to be bidirectional, with some sediment depositing at Vermilion and some at Beaver Park Marina. At Beaver Park Marina prior to the construction of the west jetty, it was assumed that sediment was transported around the marina from west into the Lorain-Beaver Park Marina cell, eventually being deposited in the Lorain Harbor west cell.

After the jetty was constructed, sediment from the Beaver Park Marina-Vermilion Cell was trapped at the marina. Additionally, there is a small component of LST that is west to east, trapping material just to the west of Vermilion Harbor

Other assumptions

1. At Beaver Park Marina after the construction of the west jetty, one-third of LST is trapped in the fillet, one-third of LST is lost offshore, and the final-third of LST continues to Lorain Harbor.
2. Outputs from the Beaver Park Marina-Vermilion Cell
    a. Pre-Armoring: 1,500 m^3/year LST to the west, remainder to the east
    b. Mid-Century: 1,100 m^3/year LST to the west, remainder to the east
    c. Recent: 800 m^3/year LST to the west, remainder to the east
    d. Future: 600 m^3/year LST to the west, remainder to the east
3. Vermilion Harbor transport
    a. Pre-Armoring: 900 m^3/year LST from Vermilion Harbor fillet cell, 300 m^3/year LST from the Vermilion-Huron cell
    b. Mid-Century: 700 m^3/year LST from Vermilion Harbor fillet cell, 300 m^3/year LST from the Vermilion-Huron cell
    c. Recent: 500 m^3/year LST from Vermilion Harbor fillet cell, 300 m^3/year LST from the Vermilion-Huron cell
    d. Future: 300 m^3/year LST from Vermilion Harbor fillet cell, 200 m^3/year LST from the Vermilion-Huron cell

Tables 18 and 19 give the predicted and measured sediment flux values at Vermilion and Lorain Harbors, respectively.

Table 18. Predicted and measured volumetric change at Vermilion Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
East	800	600	500	400	400	900	400
West	1,200	900	1,000	900	800	300	500
Total	2,000	1,500	1,500	1,300	1,200	1,200	900
	Total Difference	500	Total Difference	200	Total Difference	0	-300
		33%		15%		0	-25%

Table 19. Predicted and measured volumetric change at Lorain Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
East	4,000	2,600	1,100	6,000	600	-200	100
West	6,200	6,800	2,200	6,600	700	4,300	200
Total	10,200	9,400	3,300	12,600	1,300	4,100	300
	Total Difference	800	Total Difference	-9,300	Total Difference	-2,800	-3,800
		31%		-155%		-68%	-93%

The SBAS cells for Vermilion Harbor, Beaver Creek Marina, and Lorain Harbor from the Pre-Armoring through the Future time frames are presented in Figures 36 through 47.

Figure 36. Vermilion Harbor Pre-Armoring sediment budget.

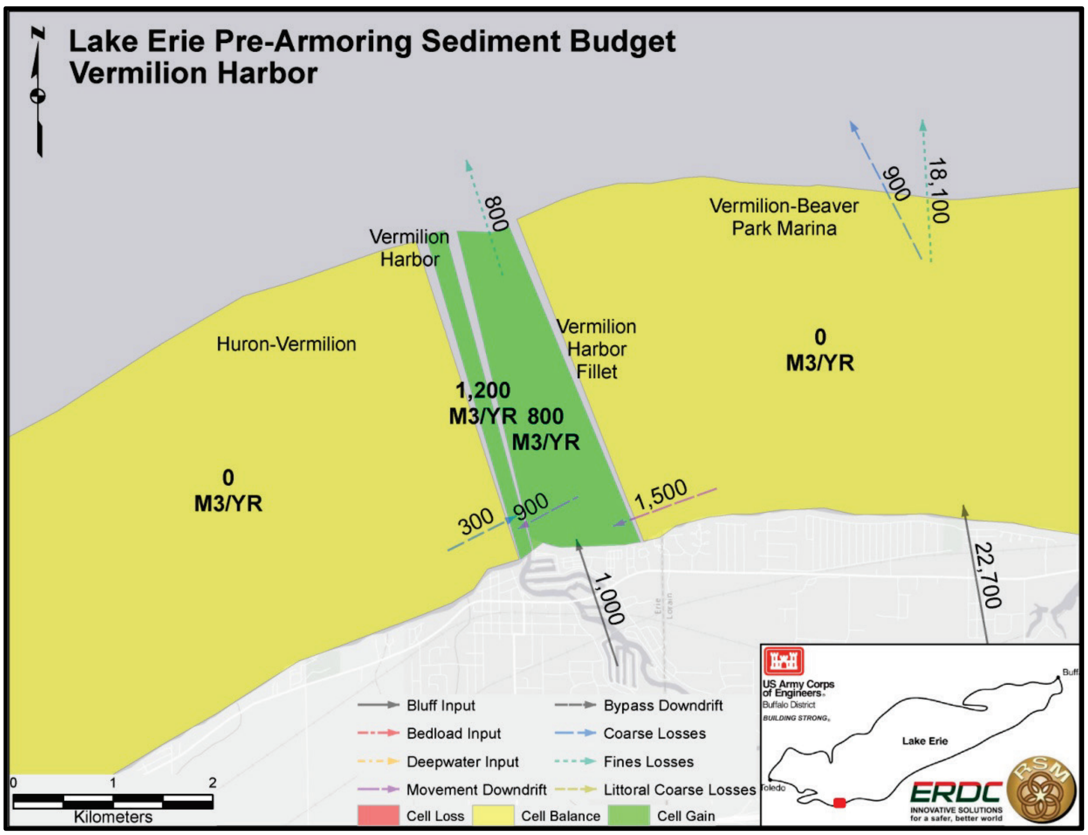


Figure 37. Vermilion Harbor Mid-Century sediment budget.

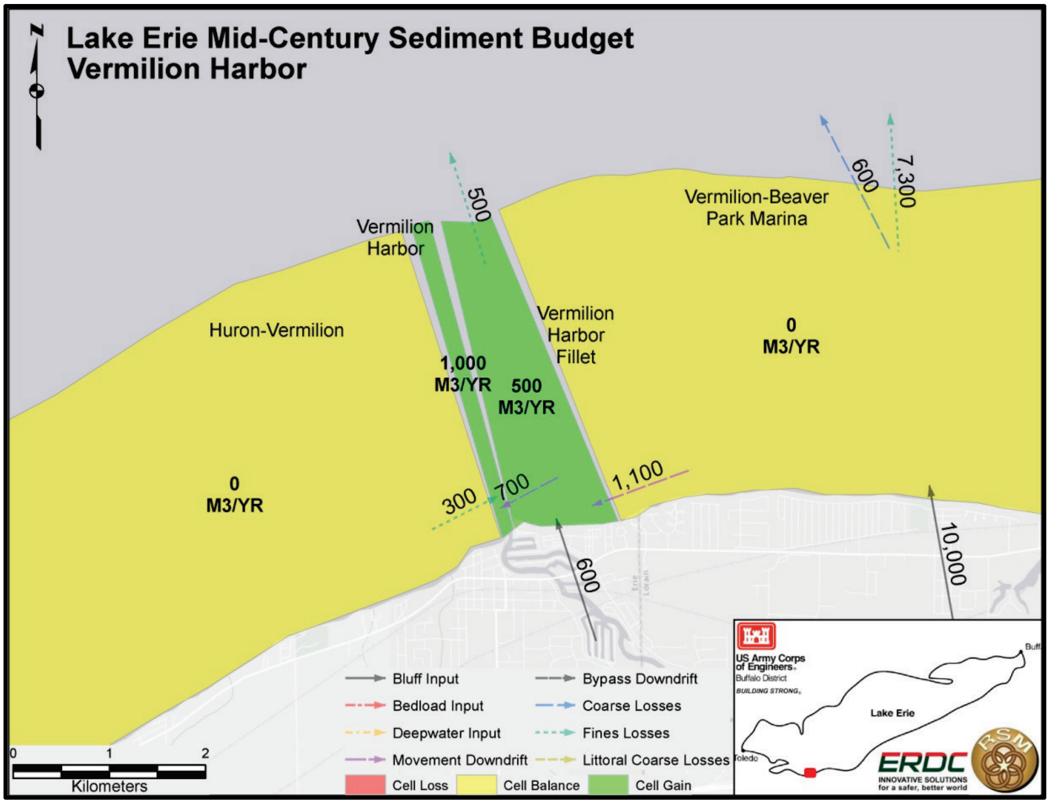


Figure 38. Vermilion Harbor Recent sediment budget.

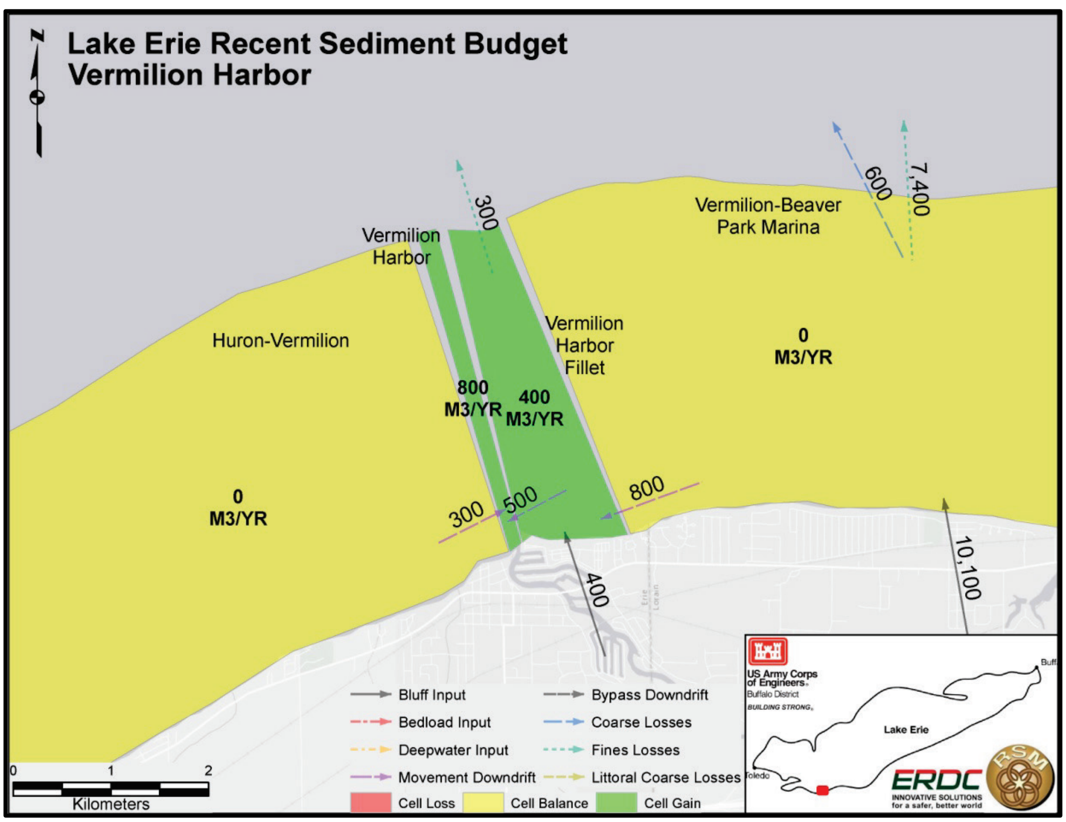


Figure 39. Vermilion Harbor Future sediment budget.

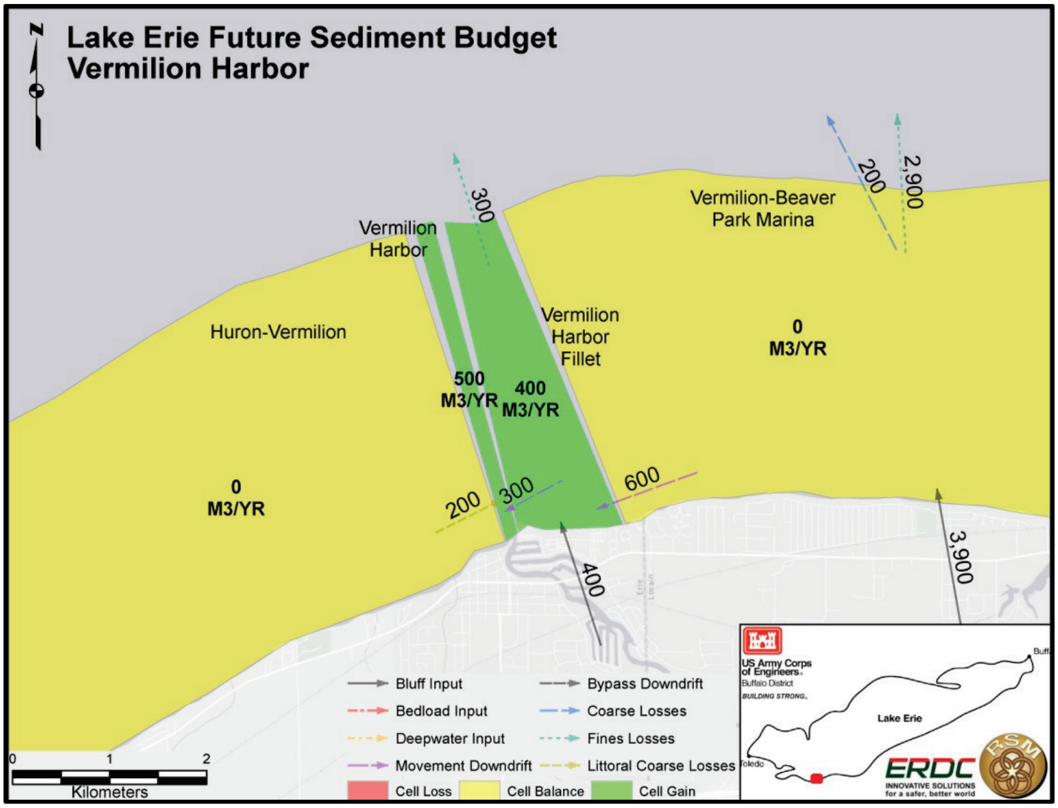


Figure 40. Beaver Park Marina Pre-Armoring sediment budget.

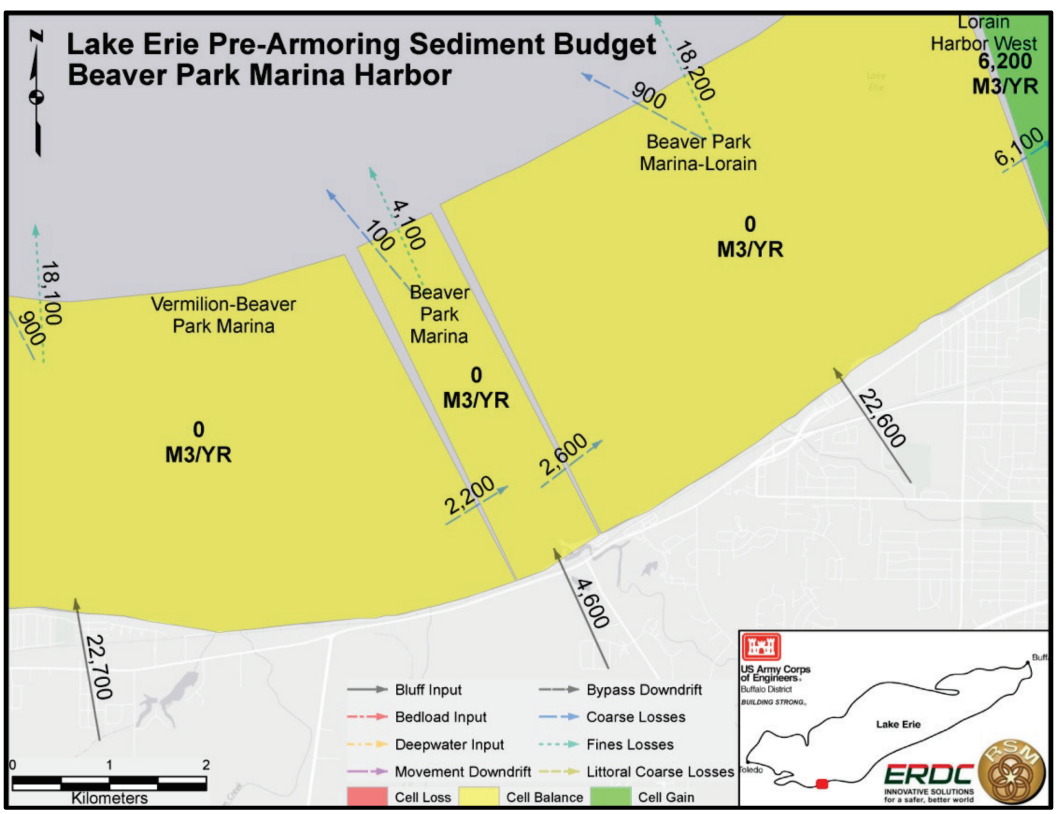


Figure 41. Beaver Park Marina Mid-Century sediment budget.

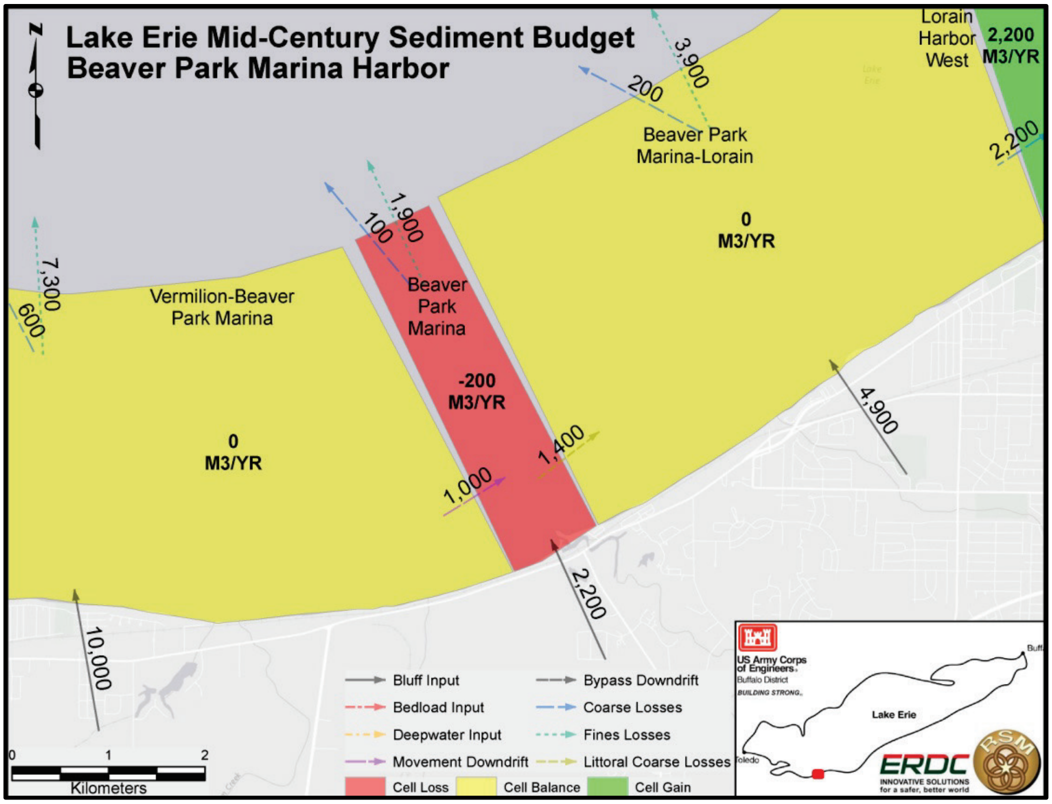


Figure 42. Beaver Park Marina Recent sediment budget.

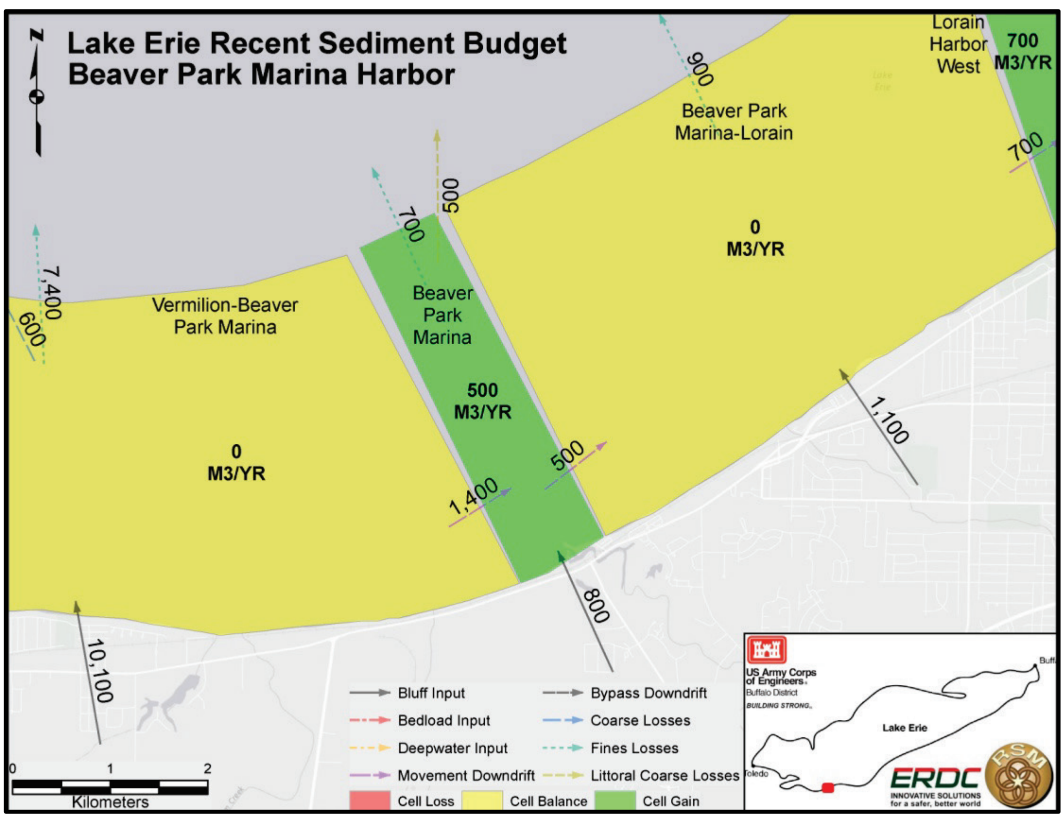


Figure 43. Beaver Park Marina Future sediment budget.

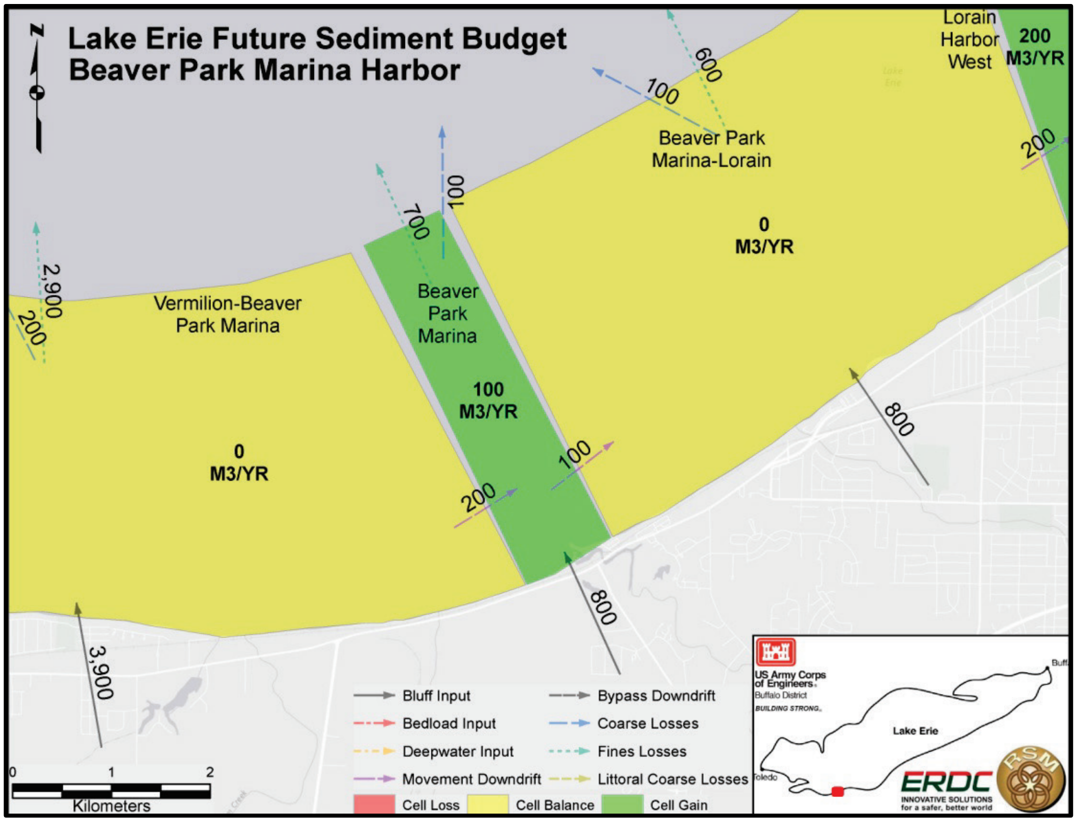


Figure 44. Lorain Harbor Pre-Armoring sediment budget.

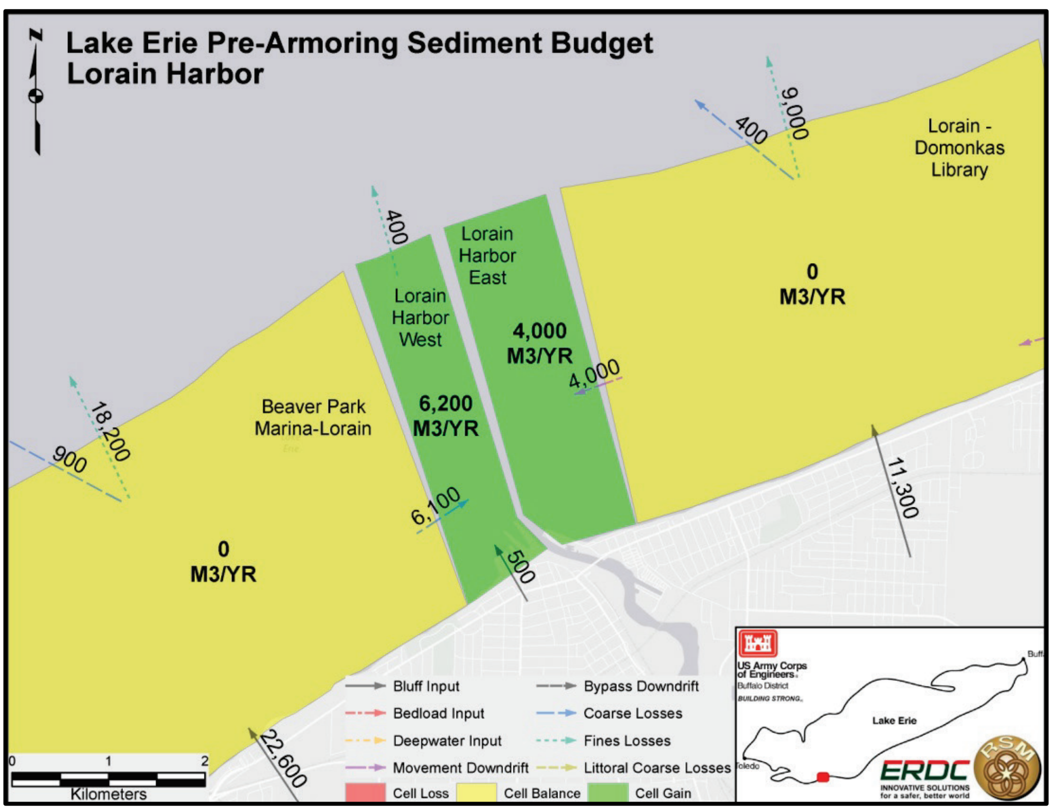


Figure 45. Lorain Harbor Mid-Century sediment budget.

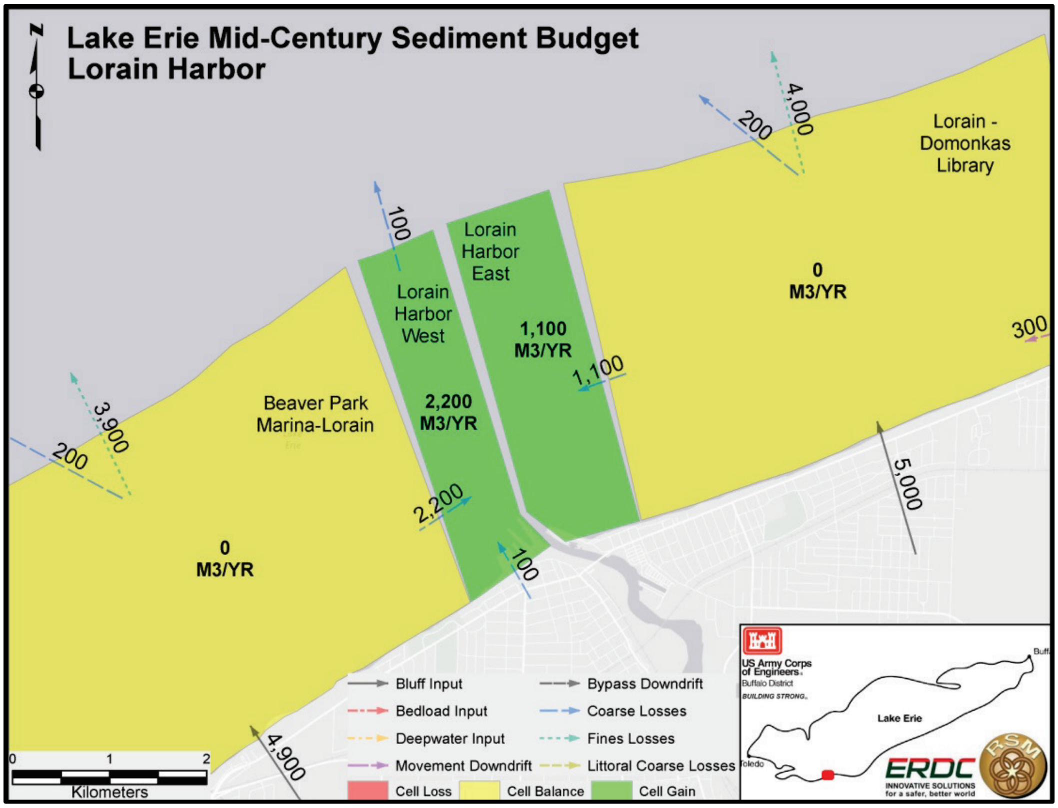


Figure 46. Lorain Harbor Recent sediment budget.

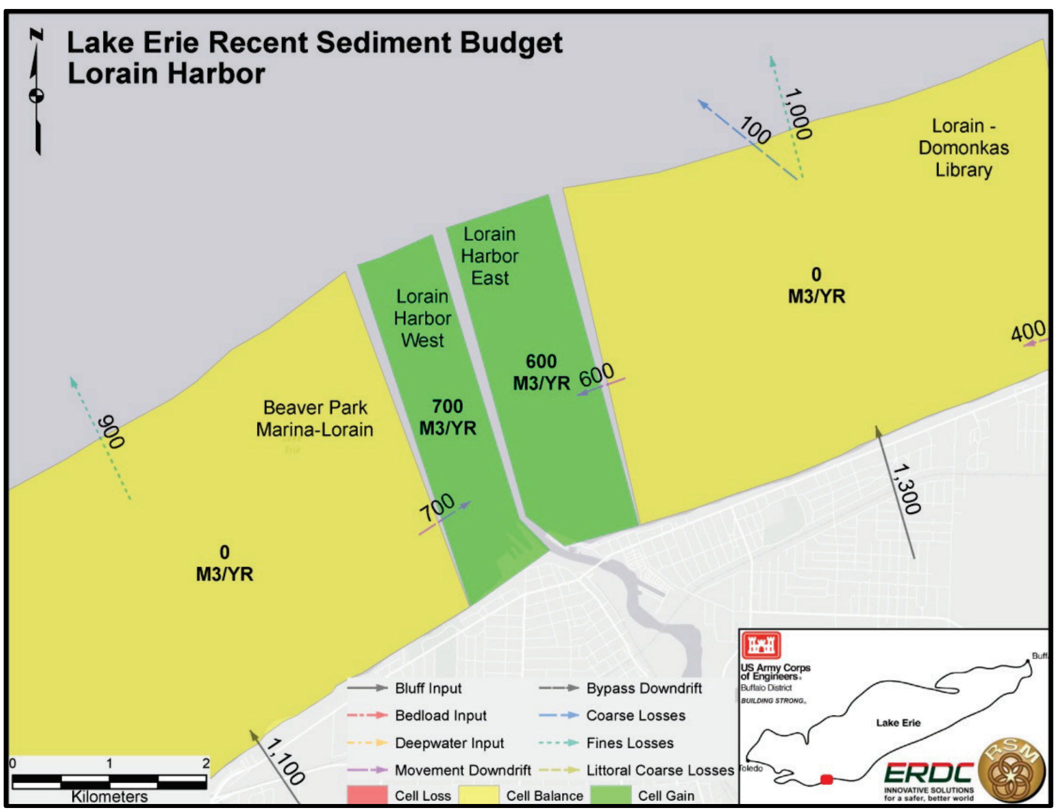
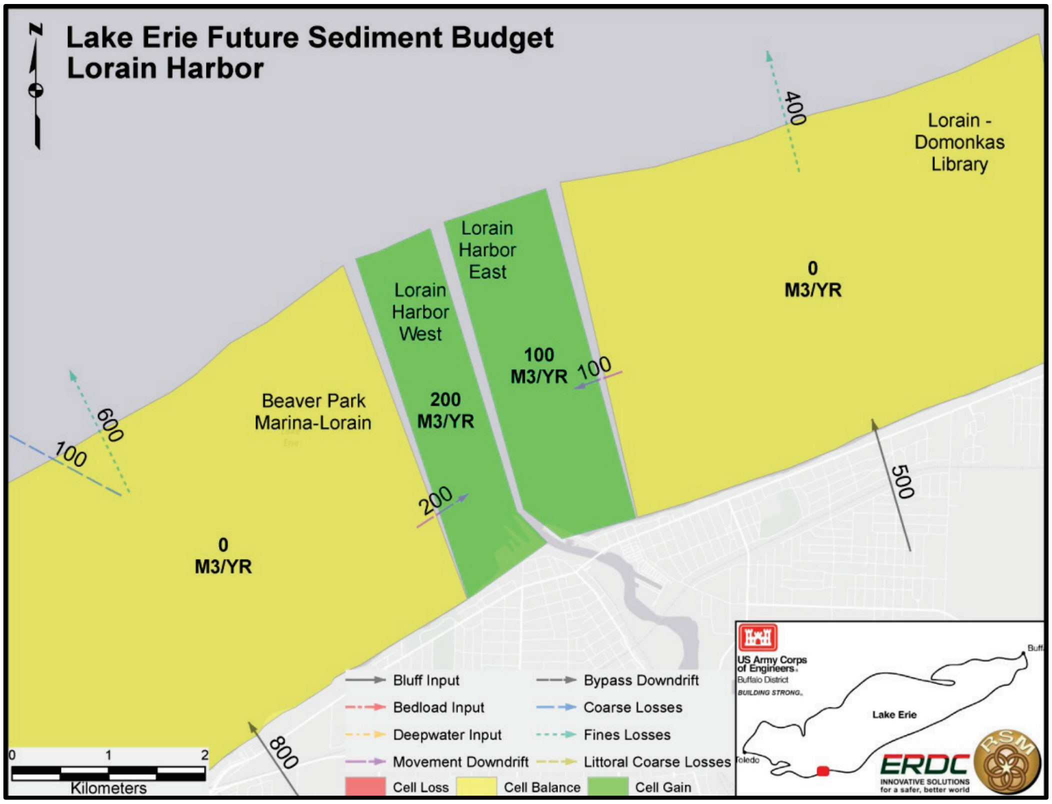


Figure 47. Lorain Harbor Future sediment budget.



Fairport Harbor, OH

Fairport Harbor structures consist of East and West Piers, and East (2,057 m long) and West (1,182 m long) Breakwaters. Construction of structures began in 1827. The earliest data used for sediment computation date to 1878.

To model the budget at Fairport, two cells were used: a fillet cell and a harbor cell (cells 41 and 42, respectively). The harbor cell has been accreting at an increasing rate since the construction of the piers, and the fillet sediments began accreting rapidly with the completion of the connection of the West Breakwater to shore in 1908. As the fillet began to fill, sediment began to pass over and through the shore-arm into the harbor. The littoral material entering Fairport Harbor from bluff recession was consistently less than measured sediment accumulation based on historic bathymetric data.

The harbor analysis at Fairport Harbor indicated a depositional rate of 55,900 m^3/year within the harbor in the Pre-Armoring time frame while sediment deposited at a rate of 5,000 m^3/year in the fillet. The bluff

analysis measured a total of 33,600 m^3/year of sediment moving into Fairport; of this, 5,000 m^3/year is modeled to have deposited within the harbor, and 28,600 m^3/year is modeled to have deposited within the fillet.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 90,000 m^3/year (85,000 m^3/year in the fillet and 5,000 m^3/year in the harbor). The bluff analysis measured a total of 23,300 m^3/year of sediment moving through the littoral system. Of this, 18,300 m^3/year was modeled to deposit in the fillet while 5,000 m^3/year was modeled to deposit in the harbor.

In the Recent time frame, the harbor analysis measured an accretion rate of 13,700 m^3/year (9,100 m^3/year in the fillet and 4,600 m^3/year in the harbor). The bluff analysis measured a total of 12,500 m^3/year of sediment moving through the system. Of this, 7,900 m^3/year was modeled to deposit within the fillet, and 4,600 m^3/year was modeled to deposit in the harbor.

In the Future time frame, the incoming sediment load will decrease to 8,000 m^3/year, with a deposition rate of 4,600 m^3/year in the fillet and 3,400 m^3/year in the harbor.

Table 20 gives predicted and measured sediment flux values at Fairport Harbor.

Table 20. Predicted and measured volumetric change at Fairport Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
Fillet	28,600	55,900	18,300	85,000	7,900	9,100	3,400
Harbor	5,000	5,000	5,000	5,000	4,600	4,600	4,600
Total	33,600	60,900	23,300	90,000	12,500	13,700	8,000
	Total Difference	-27,300	Total Difference	-66,700	Total Difference	-1,200	-5,700
		-45%		-74%		-9%	-42%

The SBAS cells for Fairport from the Pre-Armoring through the Future time frames are presented in Figures 48 through 51.

Figure 48. Fairport Harbor Pre-Armoring sediment budget.

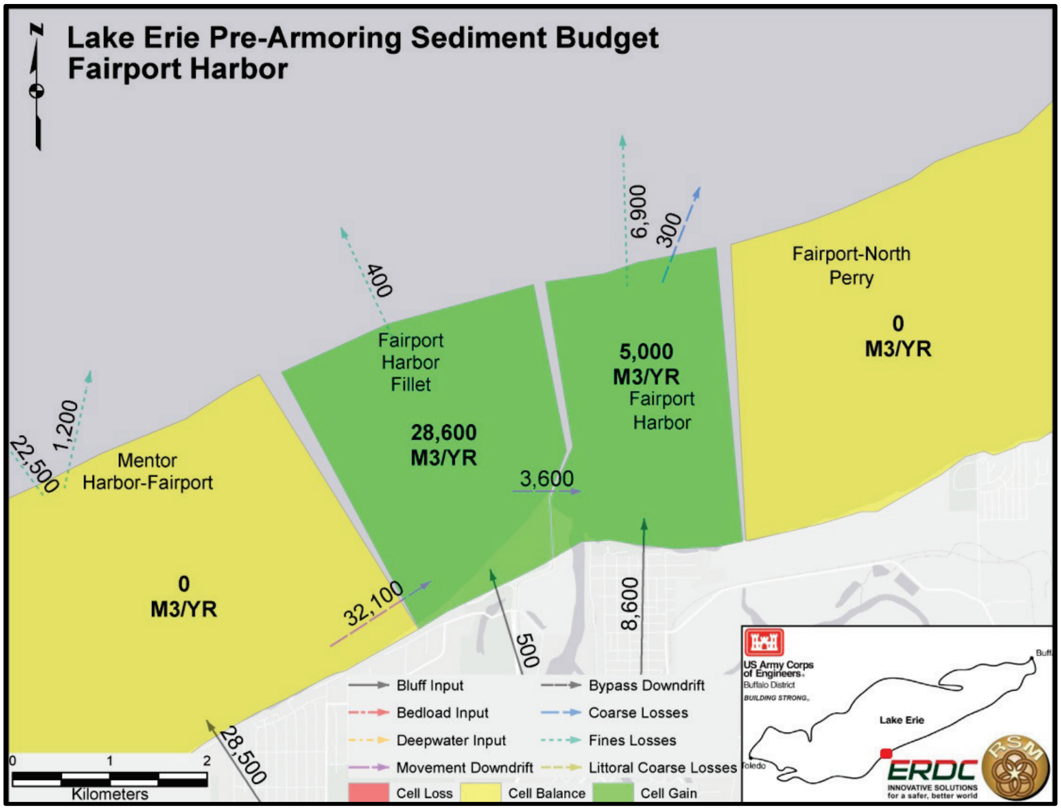


Figure 49. Fairport Harbor Mid-Century sediment budget.

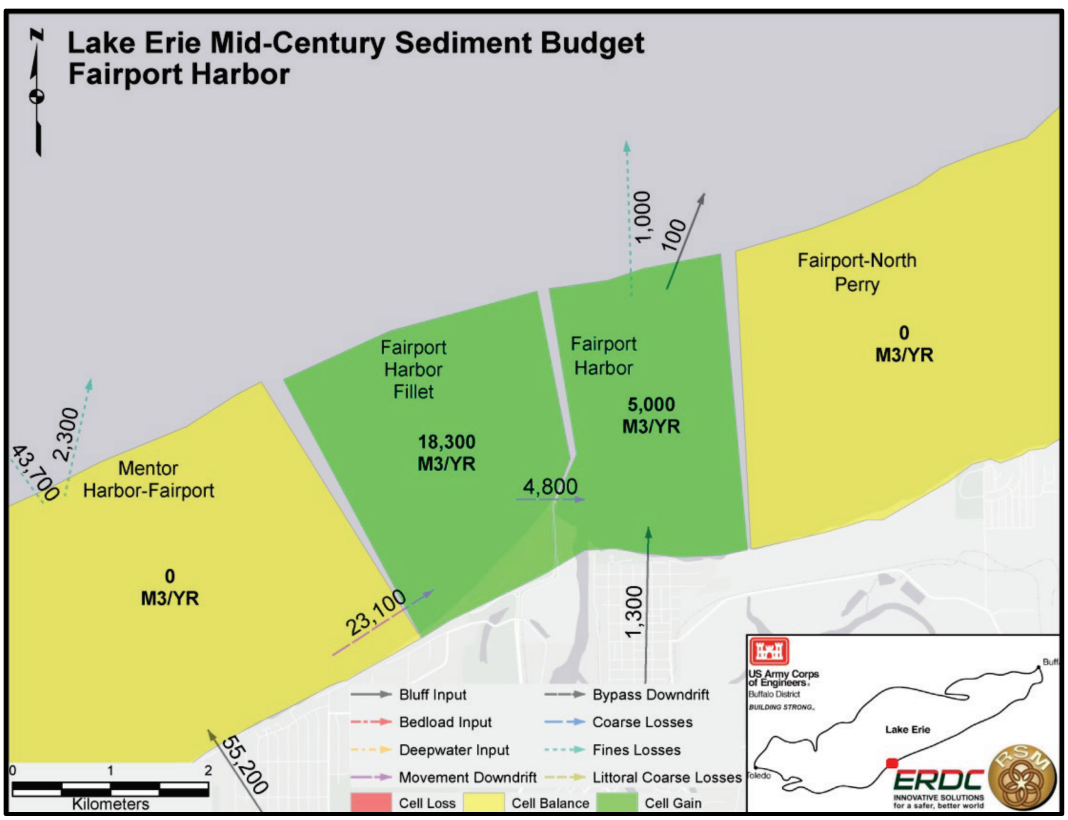


Figure 50. Fairport Harbor Recent sediment budget.

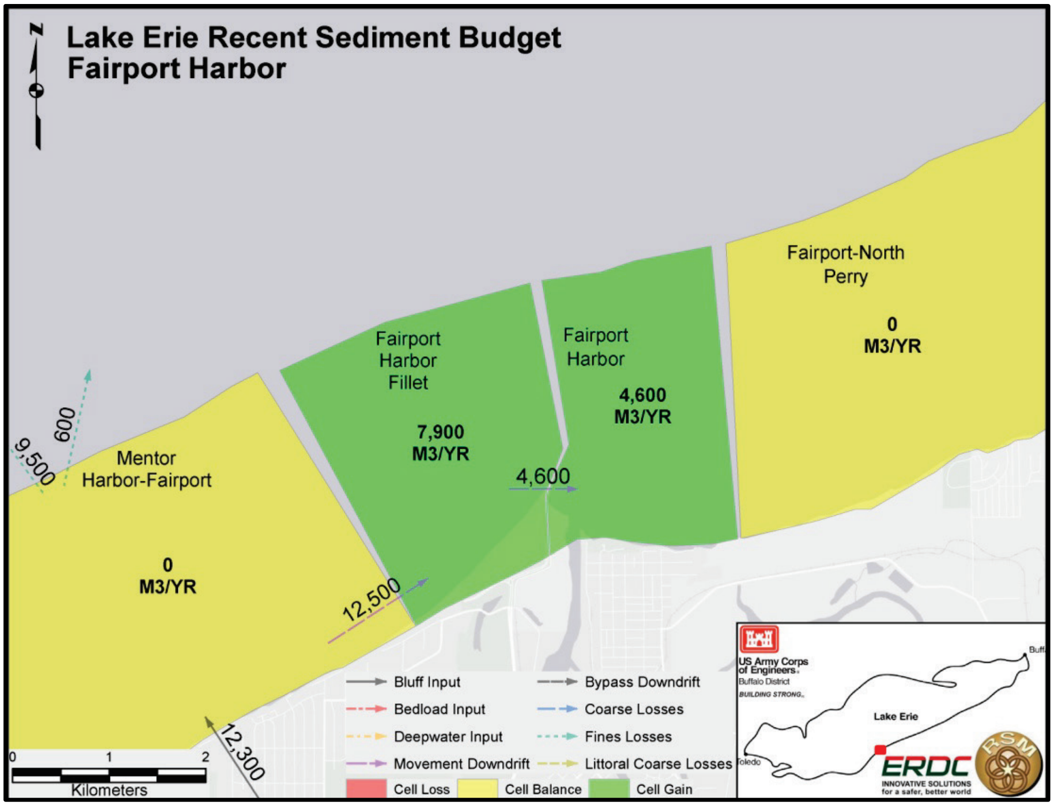
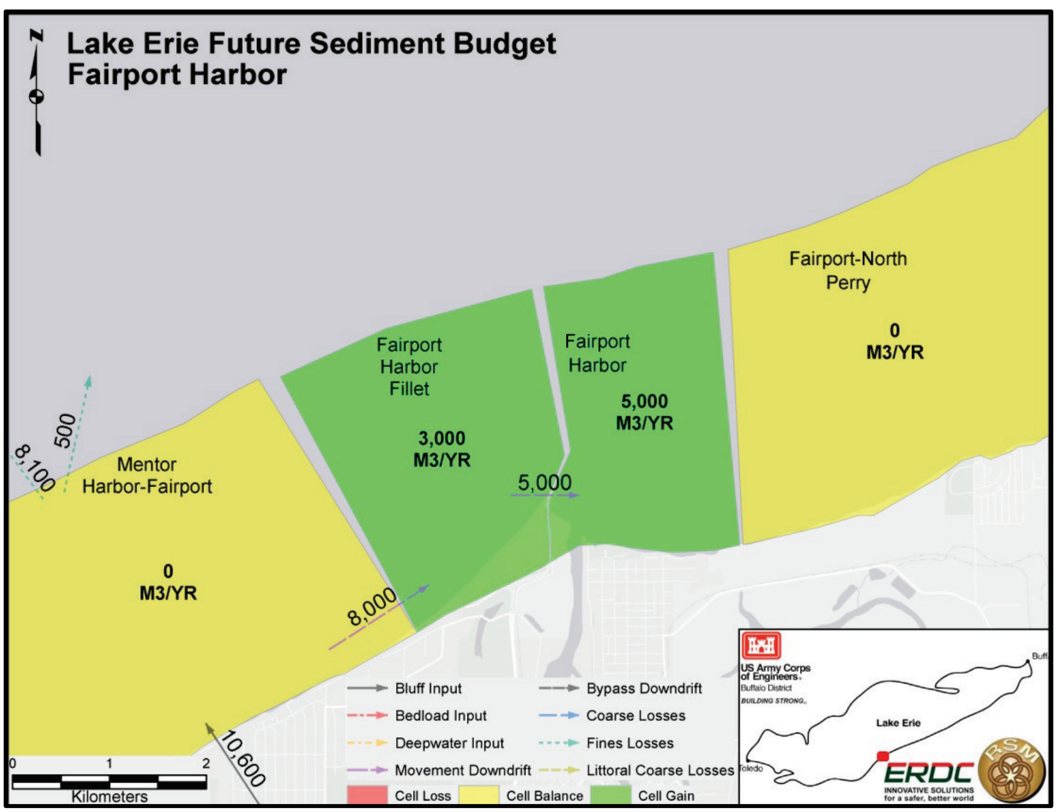


Figure 51. Fairport Harbor Future sediment budget.



Geneva-on-the-Lake Harbor, OH

Geneva-on-the-Lake Harbor structures consist of shore-attached east and west breakwaters (aggregated length 505 m). Breakwater construction was completed between 1986 to 1987. To model the budget at Geneva-on-the-Lake Harbor, two cells were used: a fillet cell and a harbor cell (cells 37 and 36, respectively). Preconstruction drawings contained bathymetric data, but the 2007 lidar flight failed to capture data below the waterline due to turbidity, so sediment accumulation could only be computed for the above-water portion of the fillet.

The Pre-Armoring and Mid-Century time frames predate the construction of the harbor, so the fillet and harbor cells did not trap any sediment. Since completion of the harbor, an average of 2,550 m^3/year has accumulated in the fillet at Geneva-on-the-Lake. As this only measured the accumulation above the waterline, 5,000 m^3/year of accretion was modeled in the fillet at Geneva-on-the-Lake Harbor, with an additional 500 m^3/year depositing in the harbor cell.

USACE (1982) predicted a total flux of 25,500 m^3/year of sediment moving through the littoral system at Geneva-on-the-Lake Harbor. This sediment budget reflects the longshore transport in the Mid-Century time frame. Because of changing shore conditions, the longshore transport rate in the Pre-Armoring time frame was assumed to be 20% greater than the Mid-Century amount.

Table 21 presents the sediment flux at Geneva-on-the-Lake Harbor from erosion of the bluffs between the harbor and Fairport Harbor, OH, and the values presented by USACE (1982) as Phase II GDM.

Table 21. Predicted and measured volumetric change at Geneva-on-the-Lake Harbor (all units in cubic meters/year).

Pre-Armoring		Mid-century		Recent		Future
Calculated Sediment from Bluffs	Phase II GDM	Calculated Sediment from Bluffs	Phase II GDM	Calculated Sediment from Bluffs	Phase II GDM	Calculated Sediment from Bluffs
37,900	30,600	45,100	25,500	44,800	25,500	34,700
Total Difference	7,300	Total Difference	19,600	Total Difference	19,300	9,200
	24%		77%		76%	36%

The SBAS cells for Geneva-on-the-Lake Harbor from the Recent and Future time frames are presented in Figures 52 and 53, respectively.

Figure 52. Geneva-on-the-Lake Harbor Recent sediment budget.

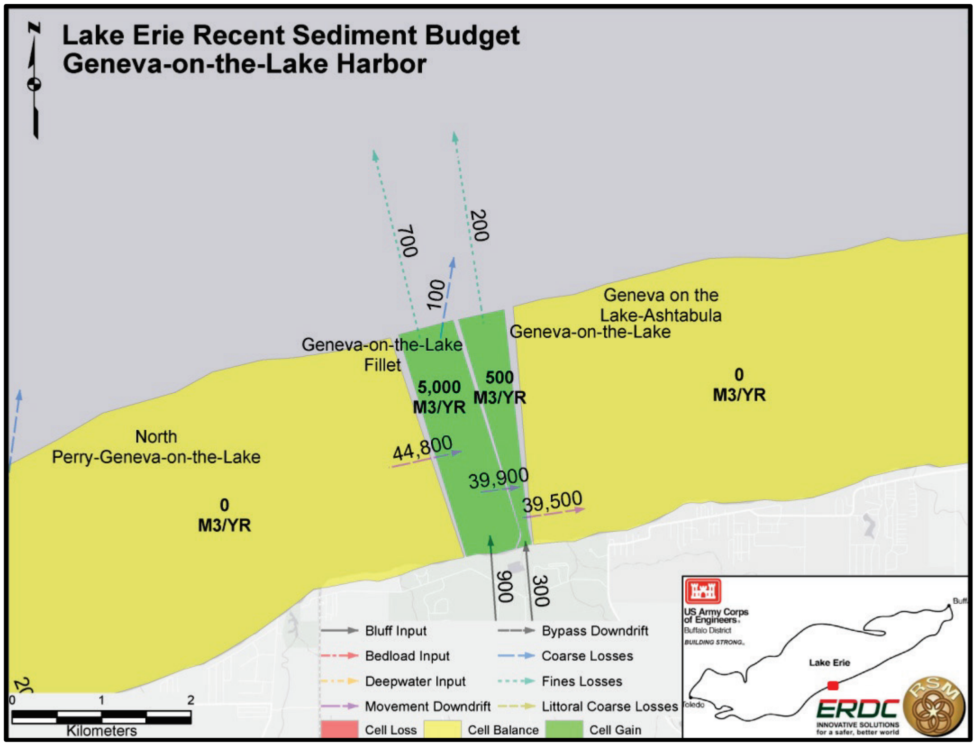
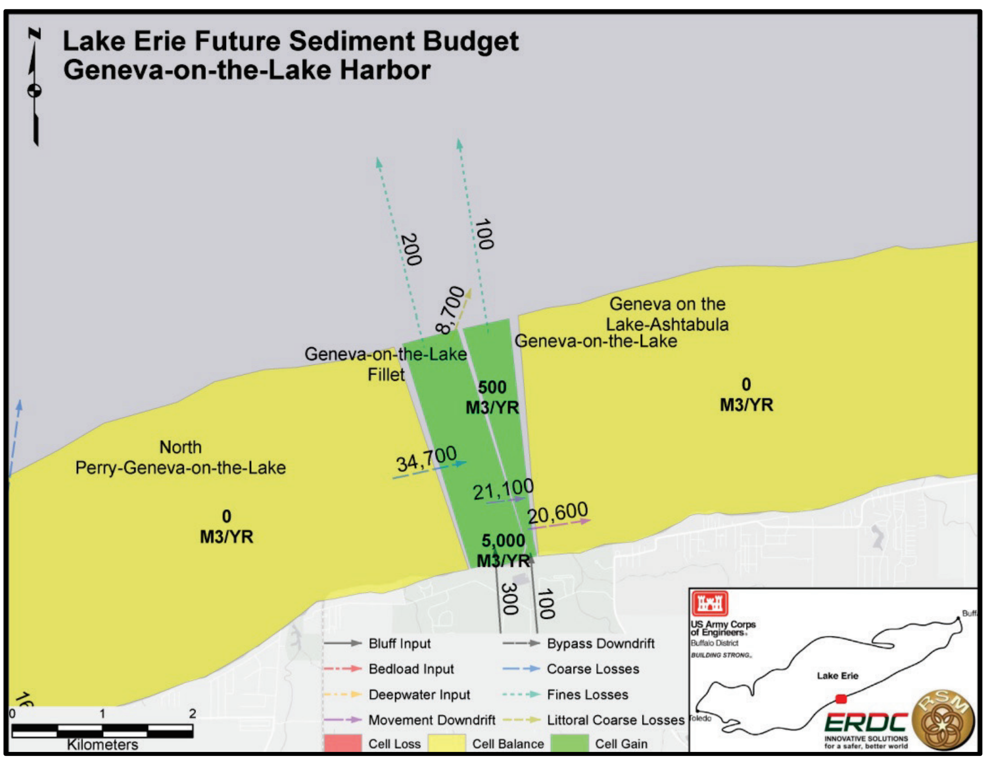


Figure 53. Geneva-on-the-Lake Harbor Future sediment budget.



Ashtabula Harbor, OH

Ashtabula Harbor structures consist of East and West piers; detached East (1,325 m long), West (2,405 m long), and Inner (425 m long) Breakwaters; and a West Shore-arm Breakwater (175 m long). Construction of structures began in 1826, and the earliest data used for sediment computation date to 1876.

To model the budget at Ashtabula Harbor, two cells were used: a fillet cell and a harbor cell (Cells 49 and 50, respectively). The harbor cell has been accreting at an increasing rate since the construction of the piers, and the fillet sediments began accreting rapidly with the completion of the West Shore-arm Breakwater in 1922. As the fillet began to fill, sediment began to pass over and through the shore-arm into the harbor. Presently, a well-developed fillet exists that has fully engulfed the shore-arm (Figure 13). This is directing a substantial amount of material along the West Breakwater and into deep water.

The harbor analysis at Ashtabula Harbor indicated a depositional rate of 21,400 m^3/year within the harbor in the Pre-Armoring time frame while sediment deposited at a rate of 5,400 m^3/year in the fillet. The bluff analysis measured a total of 48,800 m^3/year of sediment moving into Ashtabula Harbor, of which 21,400 m^3/year is modeled to have deposited within the harbor, 8,000 m^3/year to have deposited within the fillet, 12,900 m^3/year to have been lost offshore, and 6,500 m^3/year continuing downdrift into the Ashtabula-Conneaut Littoral Cell.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 23,600 m^3/year: 14,900 m^3/year in the fillet and 8,700 m^3/year in the harbor. The bluff analysis measured a total of 52,300 m^3/year of sediment moving through the littoral system. Of this, 18,000 m^3/year was modeled to deposit in the fillet while 10,000 m^3/year was modeled to deposit in the harbor. As the fillet grew, an increasing amount of sediment was redirected along the West Breakwater into deep water and thereby lost from the system, representing the additional 24,300 m^3/year of littoral material.

In the Recent time frame, the harbor analysis measured an accretion rate of 14,700 m^3/year: 5,100 m^3/year in the fillet and 9,600 m^3/year in the harbor. The bluff analysis measured a total of 46,000 m^3/year of sediment moving through the system. Of this, 6,000 m^3/year was modeled to

deposit within the fillet, and 10,000 m^3/year was modeled to deposit in the harbor with the remaining 30,000 m^3/year lost from the system into deep water.

For the Future time frame, the incoming sediment load decreases to 24,800 m^3/year. As the fillet and harbor have filled in, the accretion rate was modeled to decrease to 5,000 and 7,500 m^3/year, respectively. The additional 12,300 m^3/year was modeled to be lost offshore.

Table 22 gives predicted and measured sediment flux values at Ashtabula Harbor.

Table 22. Predicted and measured volumetric change at Ashtabula Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	**Calculated Rate from Harbor Analysis**	**Calculated Sediment from Bluffs**	**Calculated Rate from Harbor Analysis**	**Calculated Sediment from Bluffs**	**Calculated Rate from Harbor Analysis**	**Calculated Sediment from Bluffs**
Fillet	8,000	5,400	18,000	14,900	6,000	5,100	5,000
Harbor	21,400	21,400	10,000	8,700	10,000	9,600	7,500
Total	29,400	26,800	28,000	23,600	16,000	14,700	12,500
	Total Difference	2,600	Total Difference	4,400	Total Difference	1,300	-2,200
		10%		19%		9%	-15%

The SBAS cells for Ashtabula Harbor from the Pre-Armoring through the Future time frames are presented in Figures 54 through 57.

Figure 54. Ashtabula Harbor Pre-Armoring sediment budget.

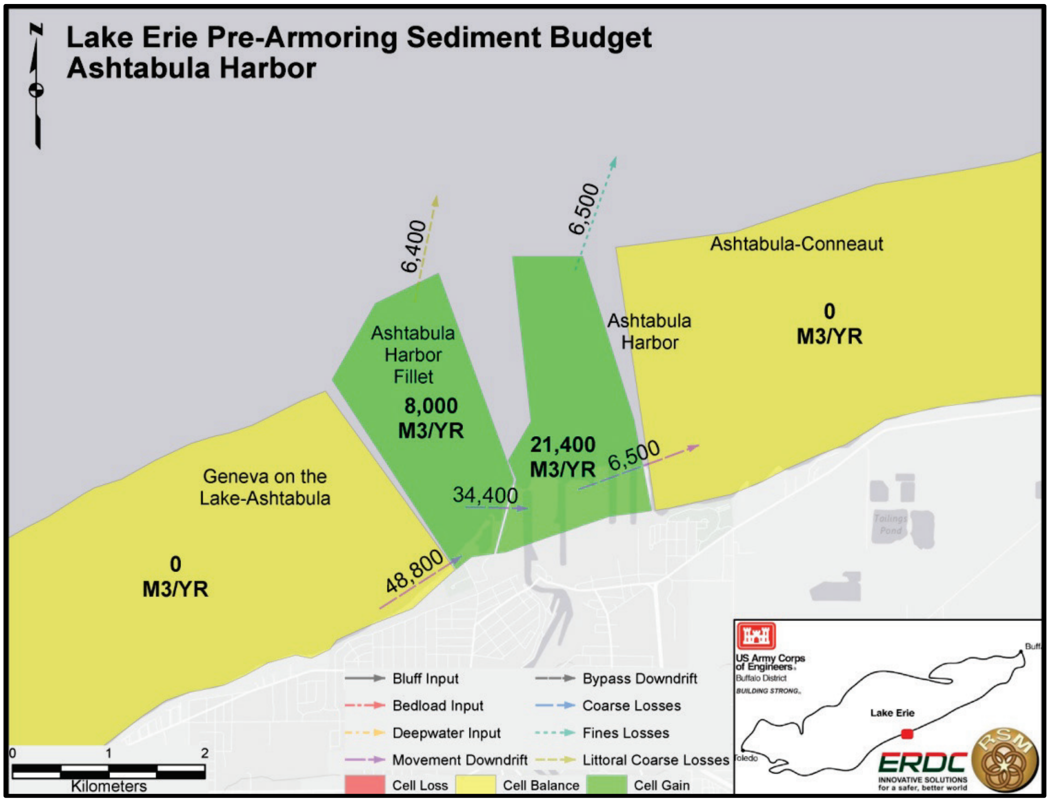


Figure 55. Ashtabula Harbor Mid-Century sediment budget.

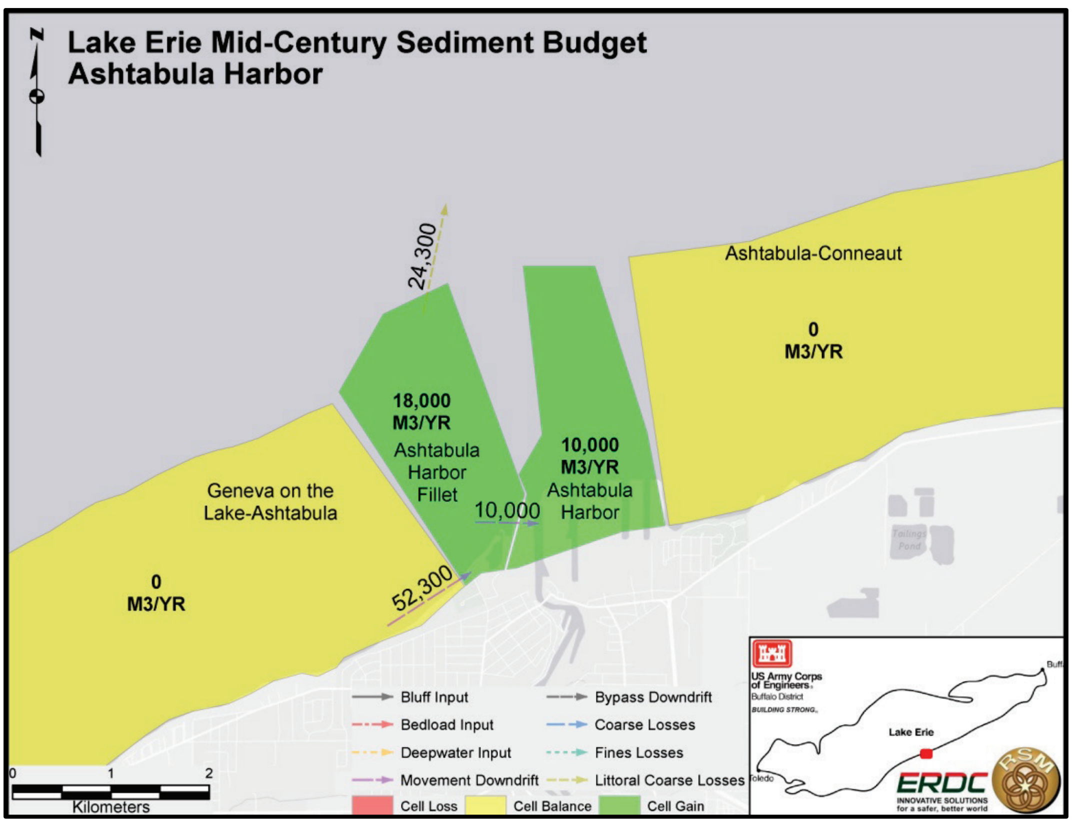


Figure 56. Ashtabula Harbor Recent sediment budget.

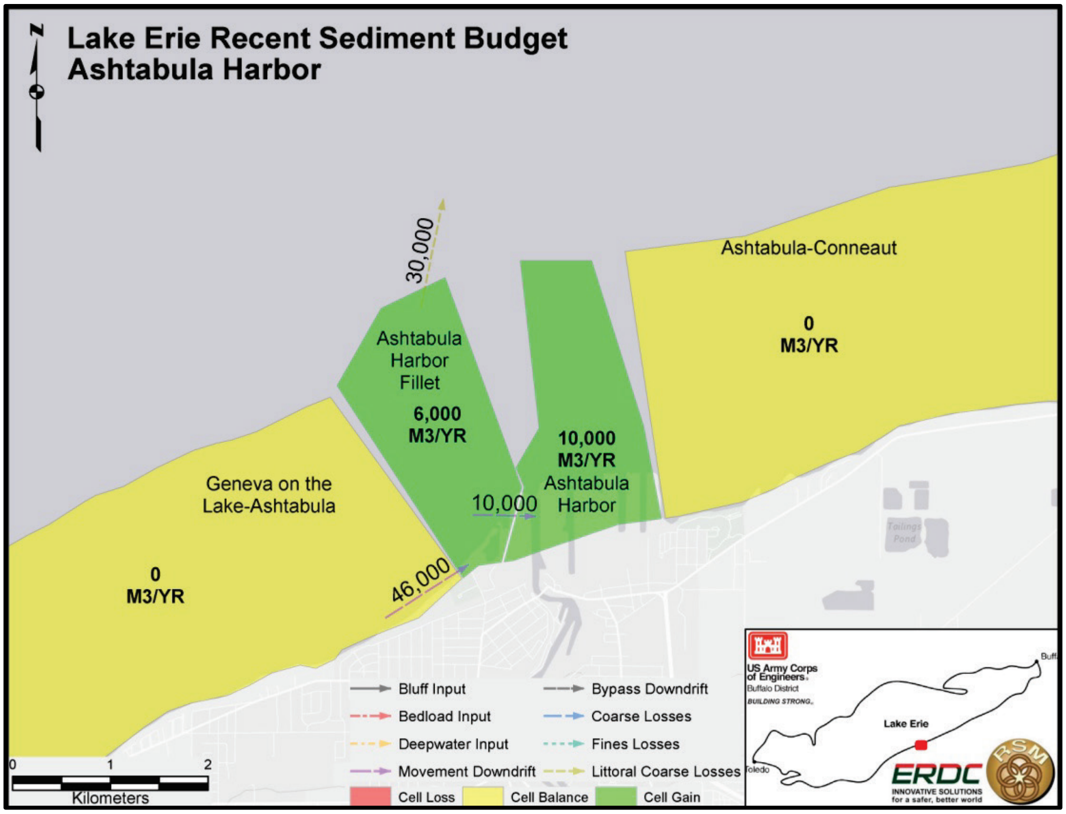
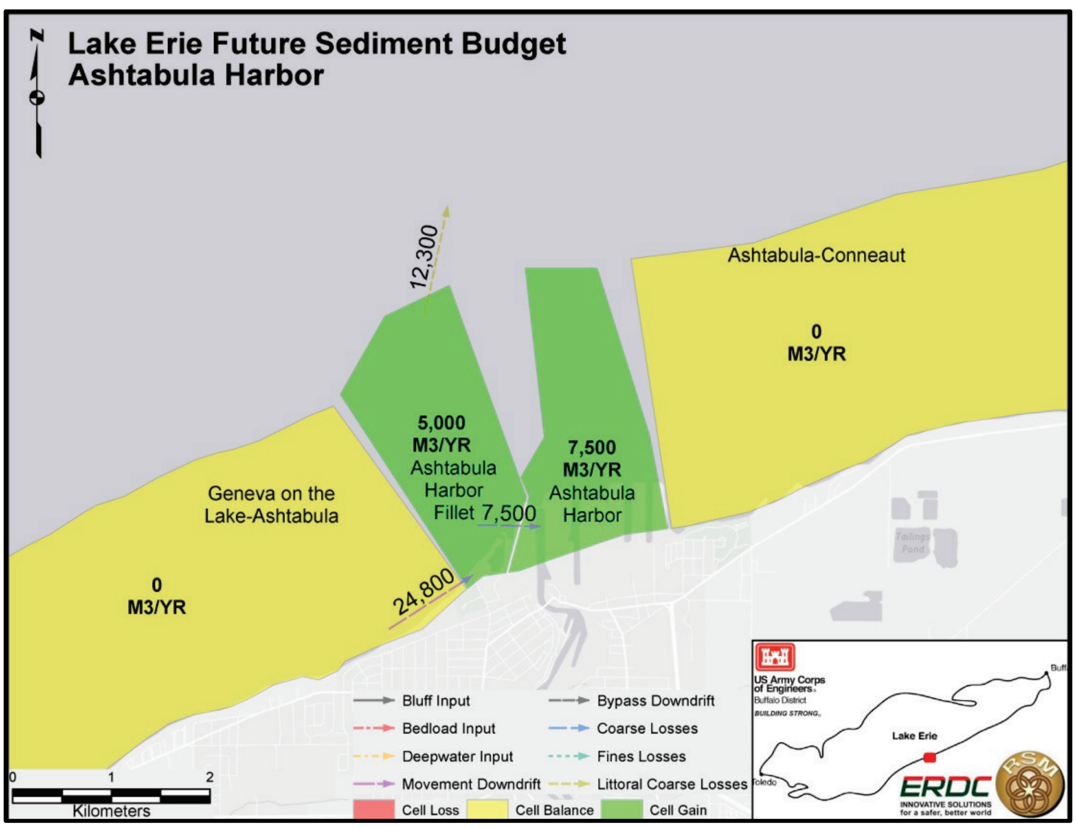


Figure 57. Ashtabula Harbor Future sediment budget.



Conneaut Harbor, OH

Conneaut Harbor structures consist of East and West Piers, detached East (1,120 m long) and West (1,810 m long) breakwaters, and East (360 m long) and West (510 m long) Shore-arm Breakwaters. Construction of structures began in 1829 and the earliest data used for sediment computation are from 1866.

To model the budget at Conneaut Harbor, two cells were used: a fillet and harbor (cells 52 and 53, respectively). The harbor cell has been accreting at an increasing rate since construction of the piers, and the fillet sediments began accreting rapidly with the completion of the West Shore-arm Breakwater in 1934. As the fillet filled, sediment began to pass over and through the shore-arm into the harbor. Presently, a well-developed fillet exists that is directing a substantial amount of material along the West Breakwater and into deep water.

The harbor analysis at Conneaut Harbor indicated a depositional rate of 7,000 m^3/year within the harbor in the Pre-Armoring time frame while the fillet remained balanced. The actual harbor depositional rate is likely higher than what was measured due to the spatial limitations of the 1866 bathymetric data. The bluff analysis measured a total of 40,800 m^3/year of sediment moving into Conneaut Harbor; of this, 10,000 m^3/year is modeled to have deposited within the harbor, 20,400 m^3/year lost offshore, and 10,300 m^3/year continued into the down-drift littoral cell.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 21,900 m^3/year (9,300 m^3/year in the fillet and 12,600 m^3/year in the harbor). The rate at the harbor is likely lower than the actual harbor sedimentation rate due to dredging. Historical dredging quantities were computed, but the data do not differentiate between dredging location, whether dredging was for maintenance purposes or expansion of the Federal harbor, or sediment type. Thus, the quantity does not give an estimate as to how much longshore drift material was removed. The bluff analysis measured a total of 25,600 m^3/year of sediment moving through the littoral system. Of this, 10,000 m^3/year was modeled to deposit in the fillet while 15,600 m^3/year was modeled to deposit in the harbor. No sediment moves beyond the harbor from Conneaut Harbor into the downdrift cell for this time frame.

In the Recent time frame, the harbor analysis measured an accretion rate of 36,600 m^3/year (5,700 m^3/year in the fillet and 30,900 in the harbor). The harbor accretion rate increased dramatically as a result of the filling of the fillet, which allowed increased sediment to pass over and around the shore-arm breakwater. In addition, a reduction of the footprint of Federal dredging at the harbor created a sediment sink. The bluff analysis measured a total of 50,500 m^3/year of sediment moving through the system. Of this, 8,000 m^3/year was modeled to deposit within the fillet, and 32,000 m^3/year was modeled to deposit in the harbor. As the fillet grew, an increased amount of sediment was redirected along the west breakwater into deep water where it was lost from the system. The remaining 10,500 m^3/year of sediment in the littoral system is modeled in this way. No sediment moves beyond the harbor from Conneaut Harbor into the downdrift cell for this time frame.

In the Future time frame, the incoming sediment load decreases to 40,400 m^3/year. As the fillet and harbor have filled in, the accretion rate was modeled to decrease to 5,000 and 25,000 m^3/year, respectively. The additional 10,400 m^3/year was modeled to be lost offshore.

Table 23 gives predicted and measured sediment flux values at Conneaut Harbor.

Table 23. Predicted and measured volumetric change at Conneaut Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
Fillet	0	0	10,000	9,300	8,000	5,700	5,000
Harbor	10,000	7,000	15,600	12,600	32,000	30,900	25,000
Total	10,000	7,000	25,600	21,900	40,000	36,600	30,000
	Total Difference	3,000	Total Difference	3,700	Total Difference	3,400	-6,600
		43%		17%		9%	-18%

The SBAS cells for Conneaut Harbor from the Pre-Armoring through the Future time frames are presented in Figures 58 through 61.

Figure 58. Conneaut Harbor Pre-Armoring sediment budget.

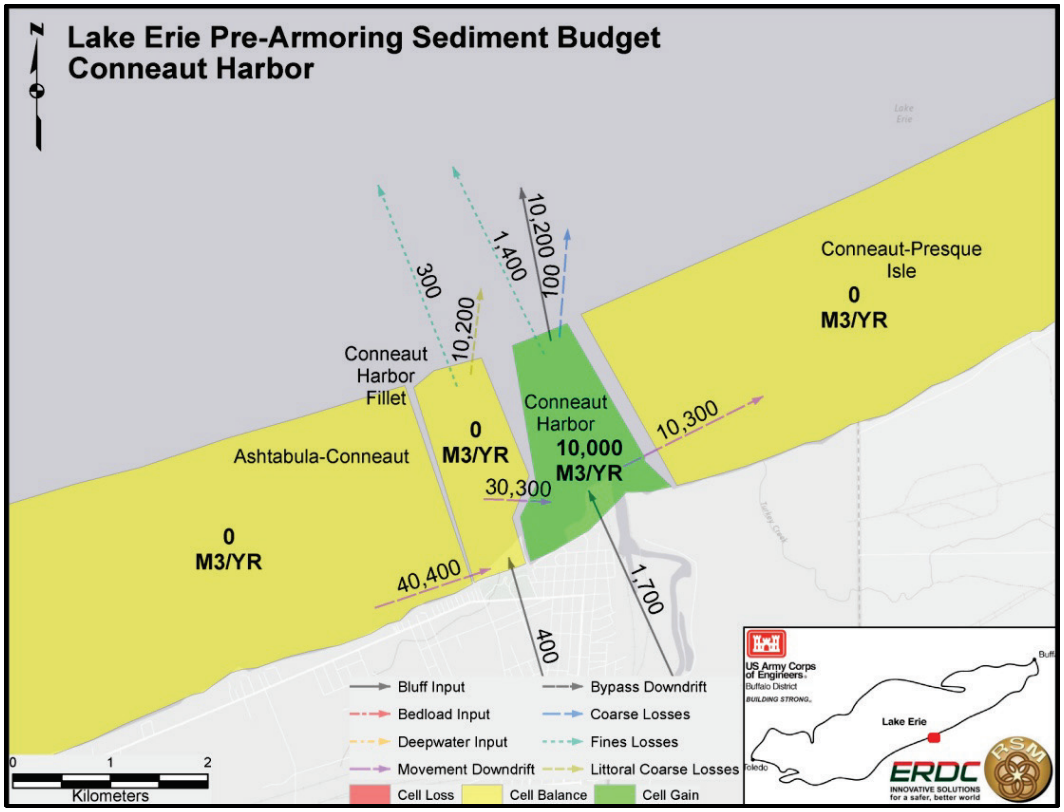


Figure 59. Conneaut Harbor Mid-Century sediment budget.

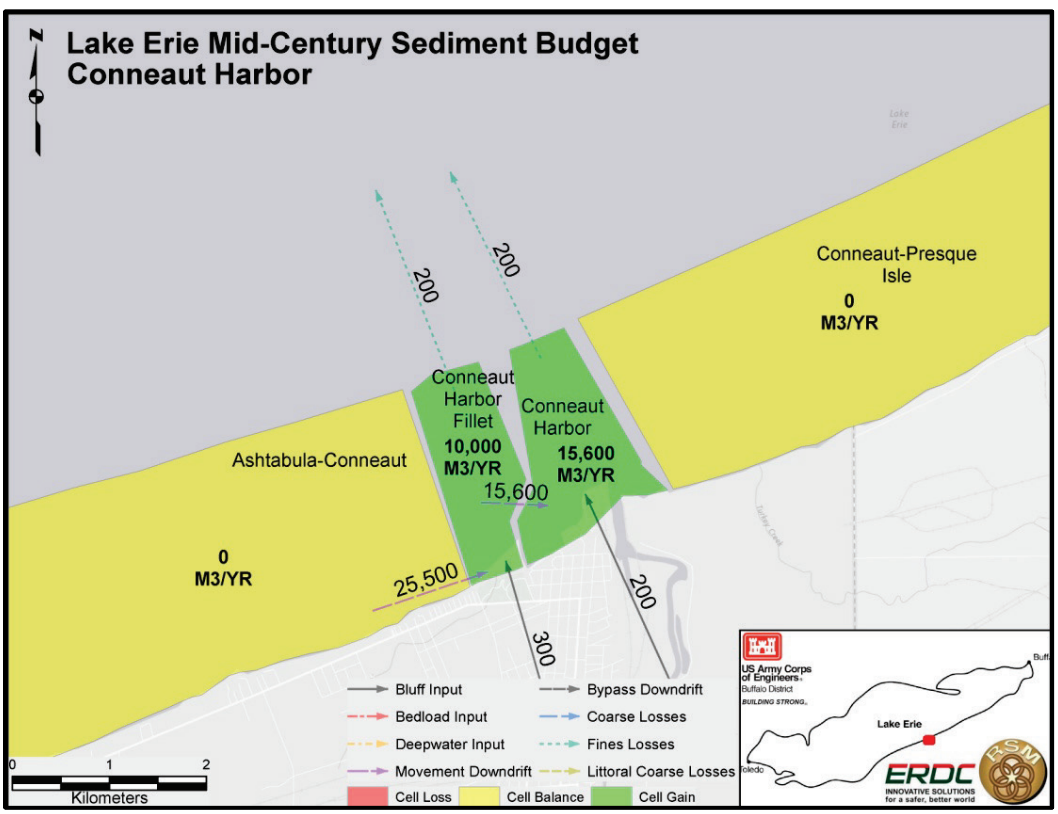


Figure 60. Conneaut Harbor Recent sediment budget.

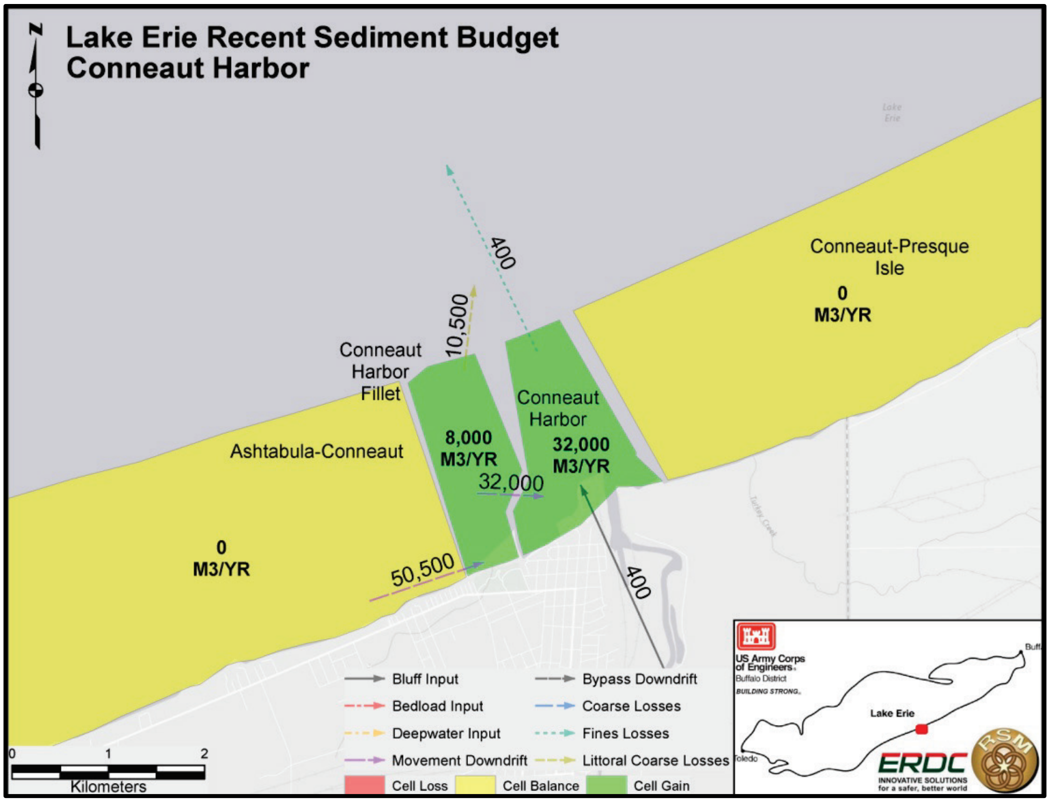
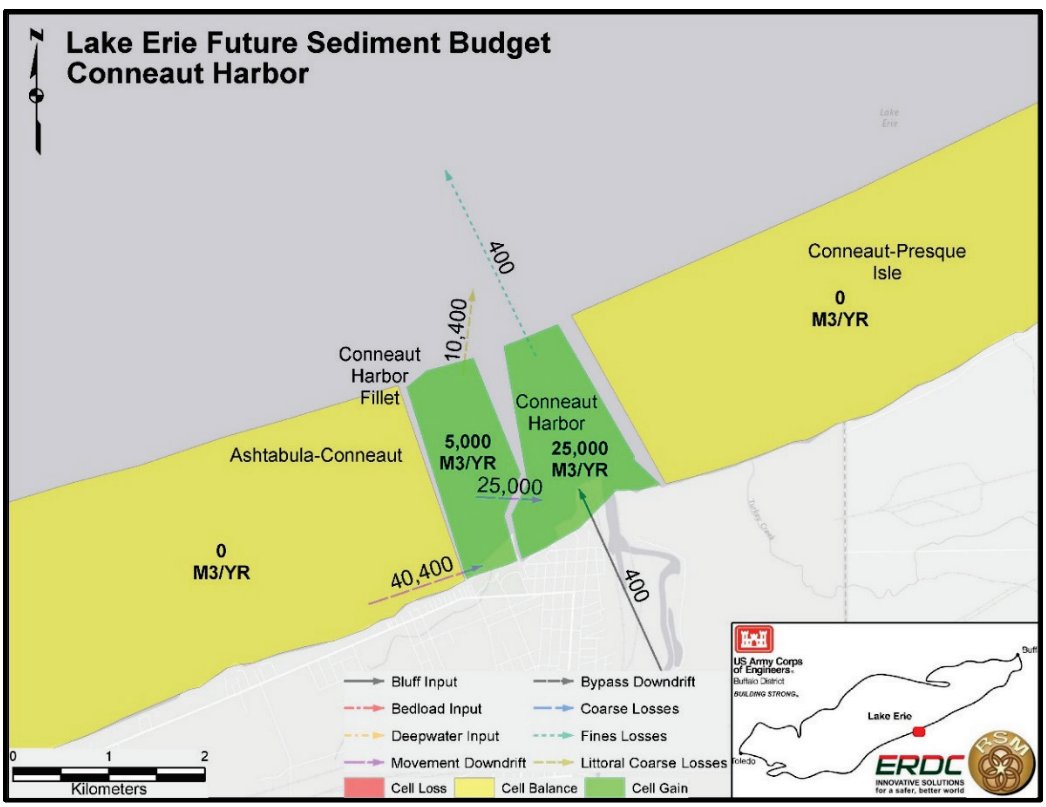


Figure 61. Conneaut Harbor Future sediment budget.



Presque Isle, PA

Presque Isle Peninsula is a natural sand spit extending into Lake Erie near Erie, PA. The spit encloses Erie Harbor and has undergone nourishment annually since 1960, with a history of erosion extending back 175 years. USACE (1984) developed sediment budgets representing the pre- and post-project conditions (Figures 62 and 63, respectively) as part of the segmented breakwater construction between October 1989 and November 1992. This sediment budget is used as the baseline comparison for the bluff erosion analysis.

Prior to completion of the breakwaters, beach nourishment at Presque Isle Peninsula averaged ~198,200 m^3/year, with an additional ~30,600 m^3/year of sand supplied by longshore transport from the west. Of this, 39,700 m^3/year was lost offshore, and ~221,000 m^3/year continued to the east as longshore transport. This left the peninsula with a predicted annual deficit of ~31,900 m^3/year.

Figure 62. Presque Isle Peninsula pre-project sediment budget (USACE 1984).

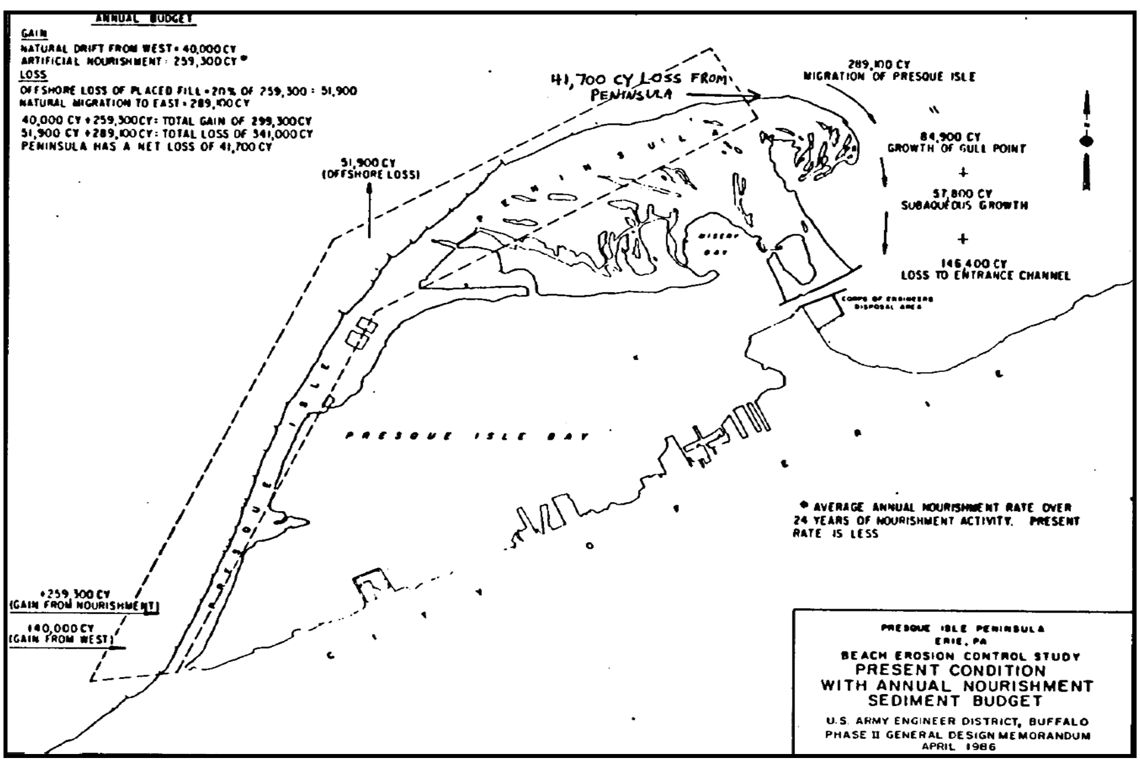
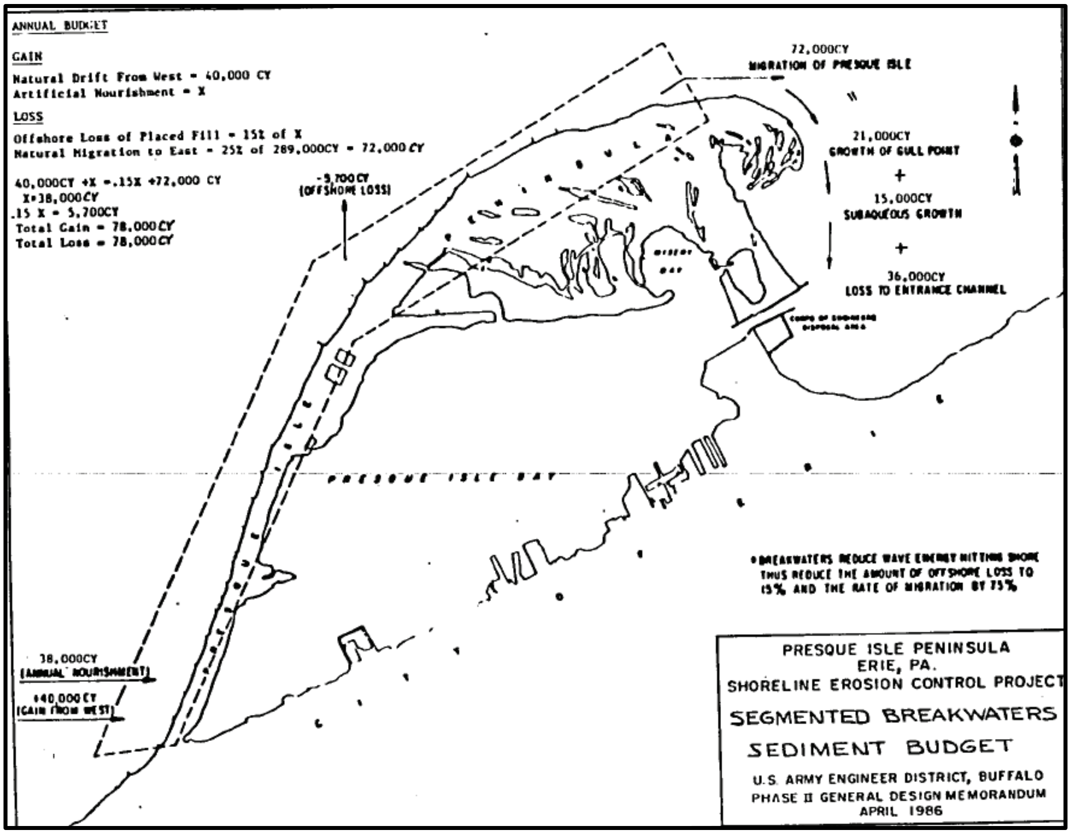


Figure 63. Presque Isle Peninsula post-project sediment budget (USACE 1984).



Post-project, the budget presented called for beach nourishment to decrease to ~29,000 m^3/year (38,000 yd^3/year), with offshore losses decreasing to ~4,400 m^3/year (5,700 yd^3/year) and longshore transport to the east decreasing to ~55,100 m^3/year (72,000 yd^3/year). Actual placement since completion of the project has averaged ~26,600 m^3/year (34,780 yd^3/year).

An important additional feature at Presque Isle Peninsula is Gull Point at the eastern end of the peninsula. Gull Point is the result of sand drifting to the east quicker than the resulting sand spit can be recurved by wave action. Gull Point did not undergo extensive growth until after the commencement of beach nourishment. Because of this, Presque Isle Peninsula was modeled in SBAS two separate ways. For the Pre-Armoring time frame, Presque Isle was modeled as a single littoral cell (cell 55) in equilibrium. For the Mid-Century, Recent, and Future time frames, a littoral cell for Gull Point was added (cell 56), and flux values were included representing nourishment, offshore loss, and longshore transport into Gull Point.

The sediment budgets presented in USACE (1984) reflect the longshore transport in the Mid-Century time frame. Because of changing shore conditions, the longshore transport rate in the Pre-Armoring time frame was assumed to be 20% greater than the Mid-Century amount. Table 24 presents the sediment flux at Presque Isle Peninsula from erosion of the bluffs between the peninsula and Conneaut, OH, and the values presented in USACE Buffalo (1984).

Table 24. Predicted and measured volumetric change at Presque Isle Peninsula (all units in cubic meters/year).

Pre-Armoring		Mid-century		Recent		Future
Calculated Sediment from Bluffs	Phase II GDM	Calculated Sediment from Bluffs	Phase II GDM	Calculated Sediment from Bluffs	Phase II GDM	Calculated Sediment from Bluffs
48,500	36,700	41,900	30,600	30,300	30,600	28,600
Total Difference	11,800	Total Difference	11,300	Total Difference	-300	-2,000
	32%		37%		-1%	-7%

The SBAS cells for Presque Isle Peninsula from the Pre-Armoring through the Future time frames are presented in Figures 64 through 67.

Figure 64. Presque Isle Peninsula Pre-Armoring sediment budget.

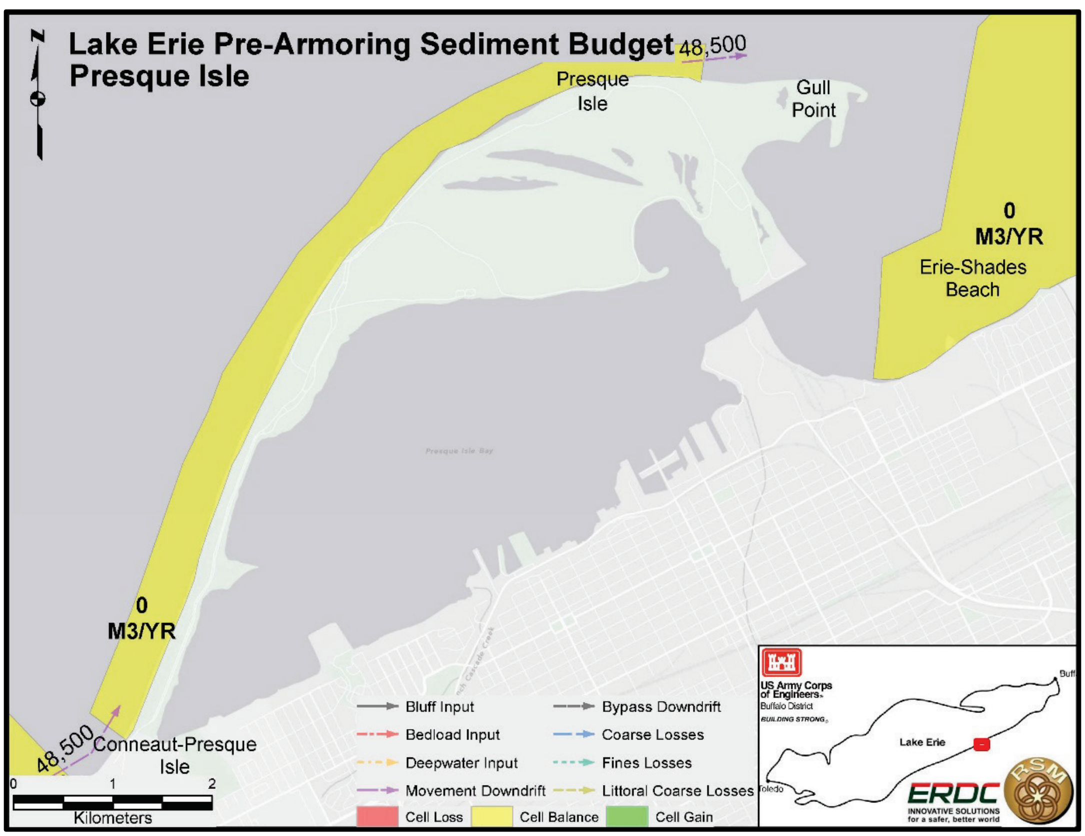


Figure 65. Presque Isle Mid-Century sediment budget.

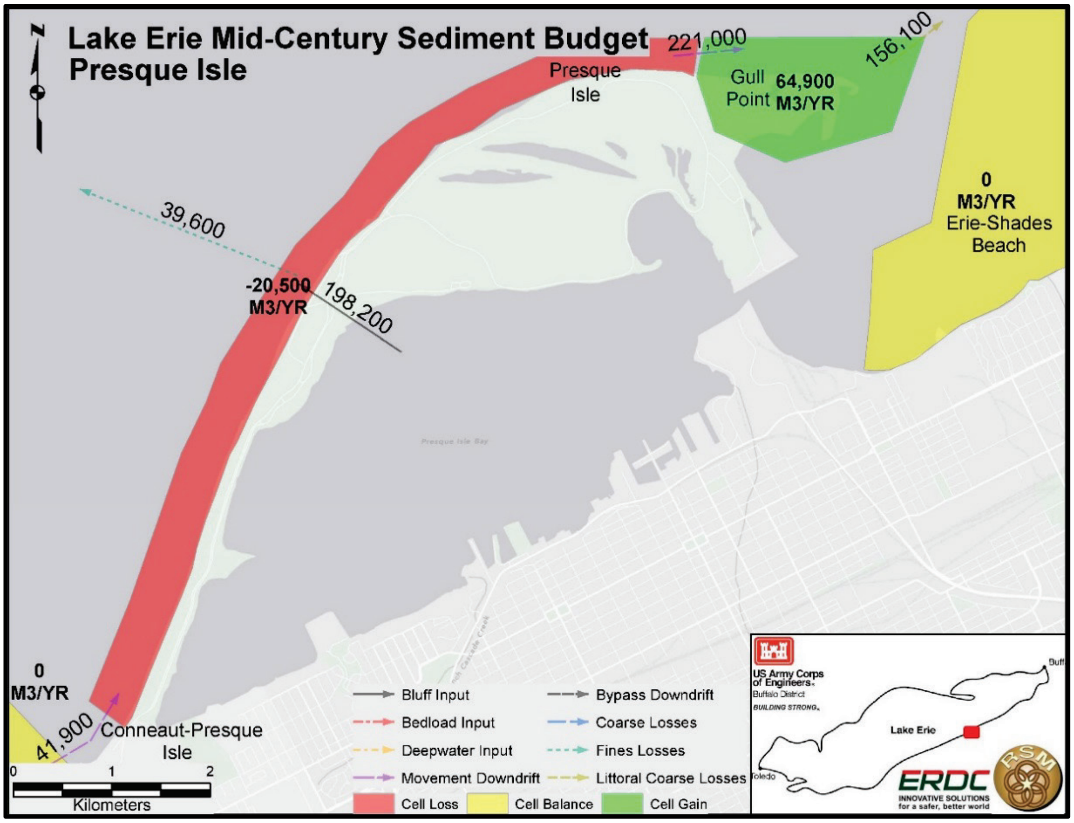


Figure 66. Presque Isle Recent sediment budget.

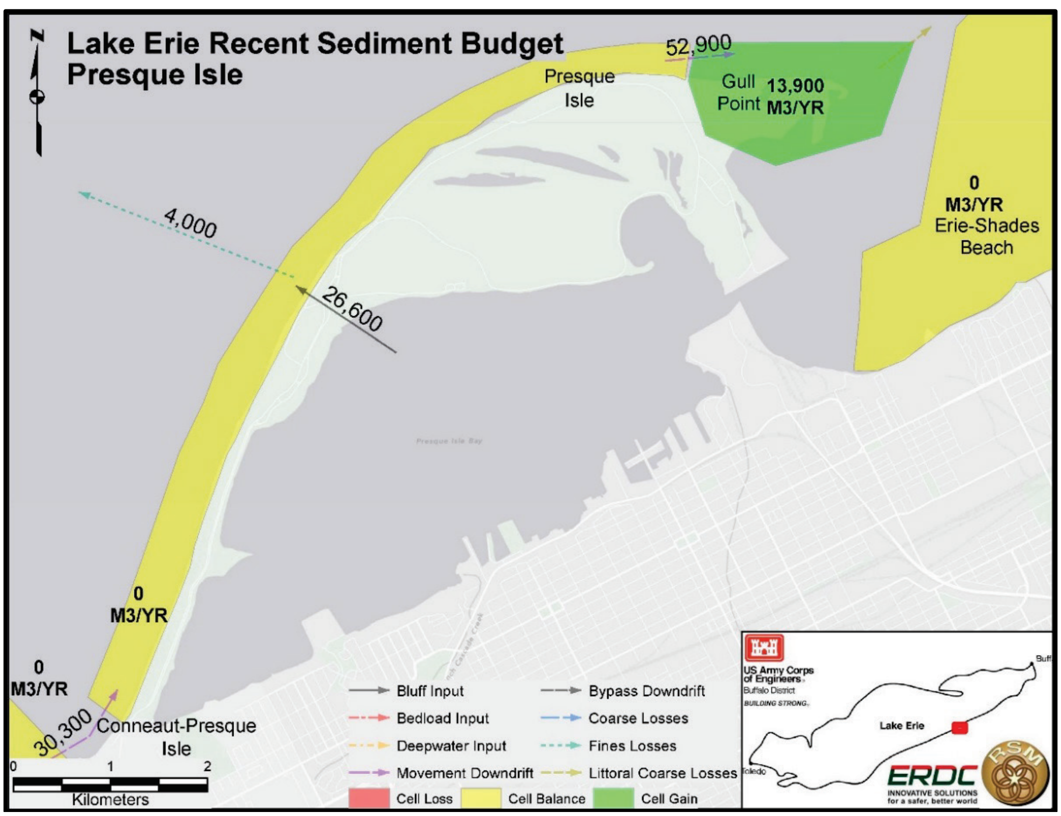
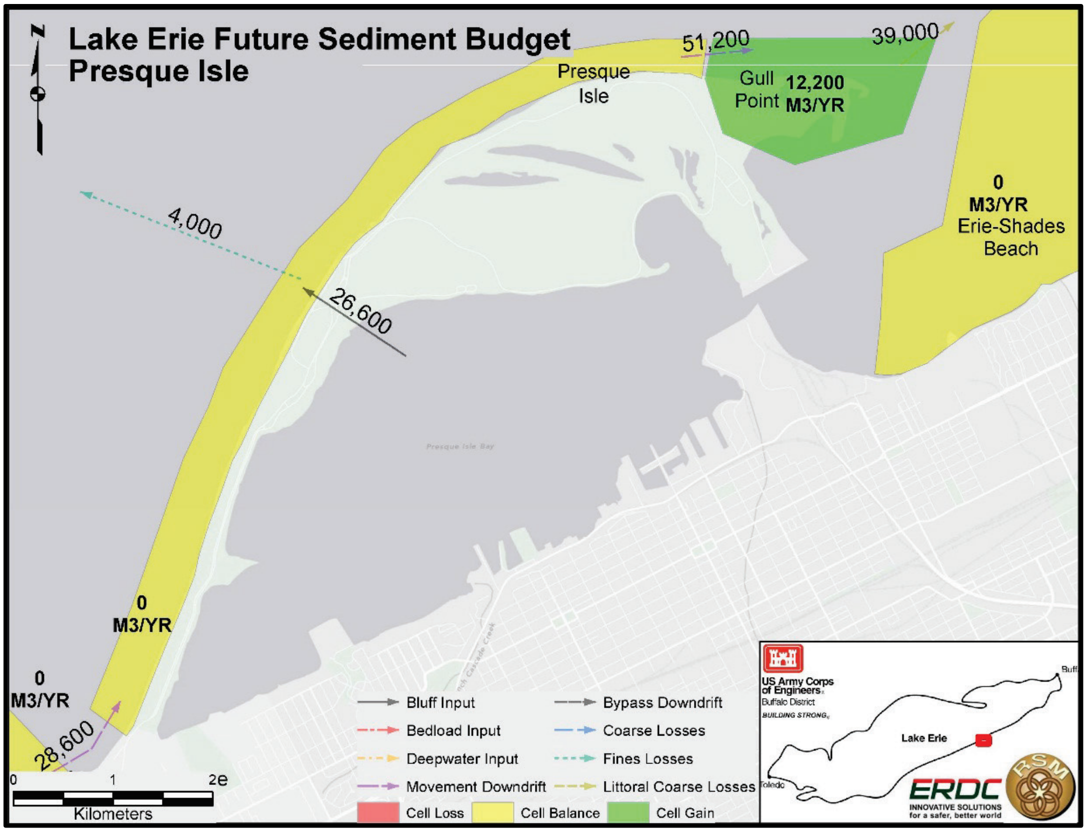


Figure 67. Presque Isle Future sediment budget.



Barcelona Harbor, NY

Barcelona Harbor structures consist of a shore-attached West Breakwater (240 m long) and a detached East Breakwater (210 m long). Breakwater construction was completed between 1958 and 1960, with modifications installed at a later date. The project was constructed at a natural headland that was redirecting sediment offshore prior to the project being built.

To model the budget at Barcelona Harbor, two cells were used: a fillet cell and a harbor cell (cells 66 and 67, respectively). It was assumed that 50% of littoral material was lost to deep water due to the headland prior to harbor development. During the Mid-Century time frame, the harbor analysis determined an accretion value approximately one-half the bluff erosion rate (5,200 m^3/year of sediment accretion from bluff erosion vs. 2,500 m^3/year measured in the fillet). This is likely due to the limited spatial extent of data available from the 1930s and 1970s. The harbor cell was also relatively balanced prior to construction of the harbor structures but has been steadily accreting since project completion. The majority of the material is transported over and around the West Breakwater;

however, because of the orientation of the harbor and the sedimentation within the harbor basin, this material is partially a result of sediment transported by storm events blowing out of the north-northeast.

Table 25 gives predicted and measured flux values at Barcelona Harbor.

Table 25. Predicted and measured volumetric change at Barcelona Harbor (all units in cubic meters/year).

	Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs
Fillet	5,200	2,500	3,500	3,100	3,000
Harbor	-100	-100	2,400	2,400	1,200
Total	5,100	2,400	5,900	5,500	4,200
	Total Difference	2,700	Total Difference	400	-1,300
		113%		7%	-24%

The SBAS cells for Barcelona Harbor from the Pre-Armoring through the Future time frames are presented in Figures 68 through 71.

Figure 68. Barcelona Harbor Pre-Armoring sediment budget.

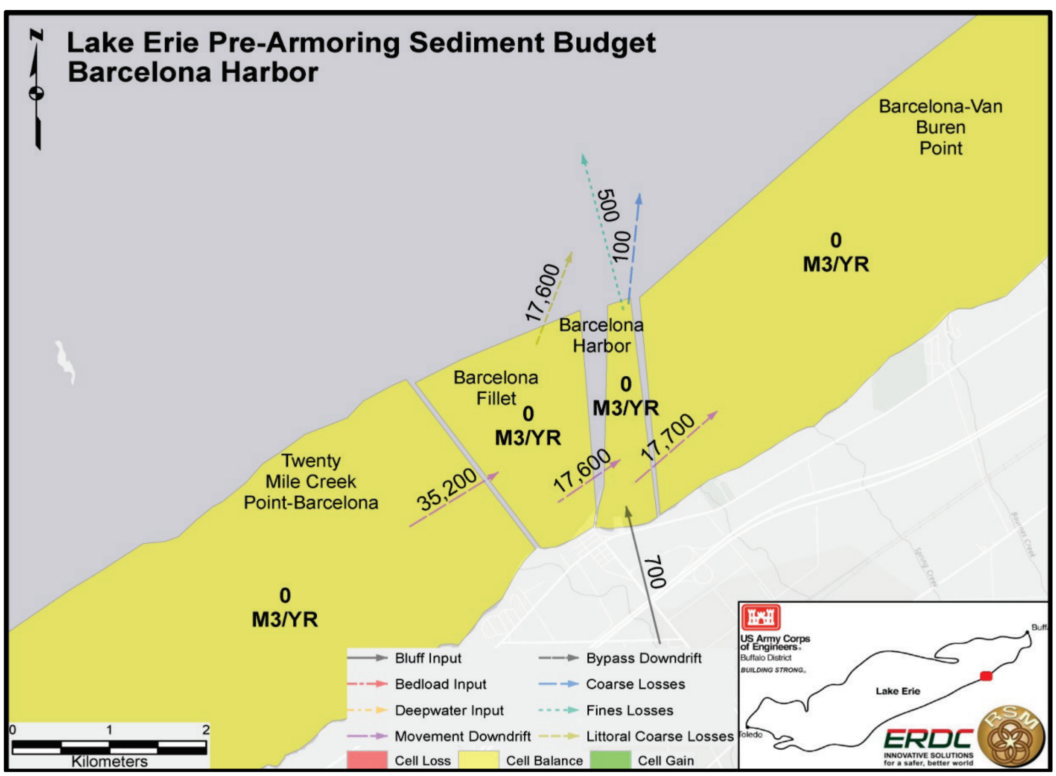


Figure 69. Barcelona Harbor Mid-Century sediment budget.

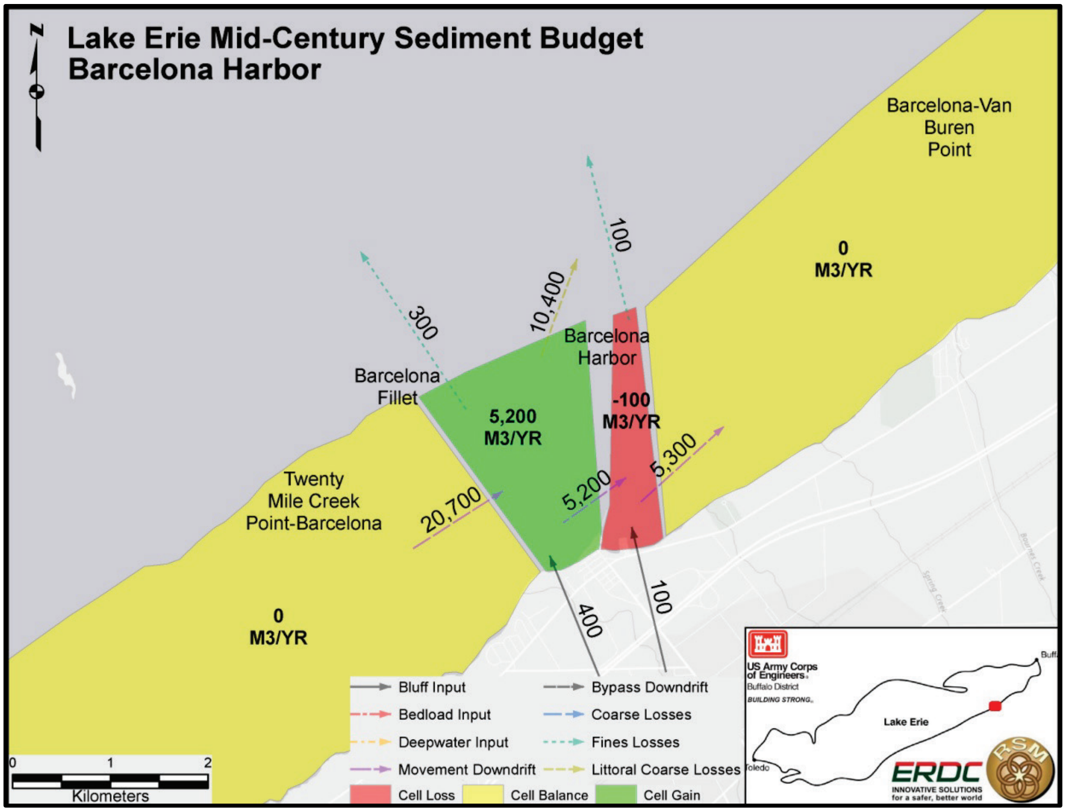


Figure 70. Barcelona Harbor Recent sediment budget.

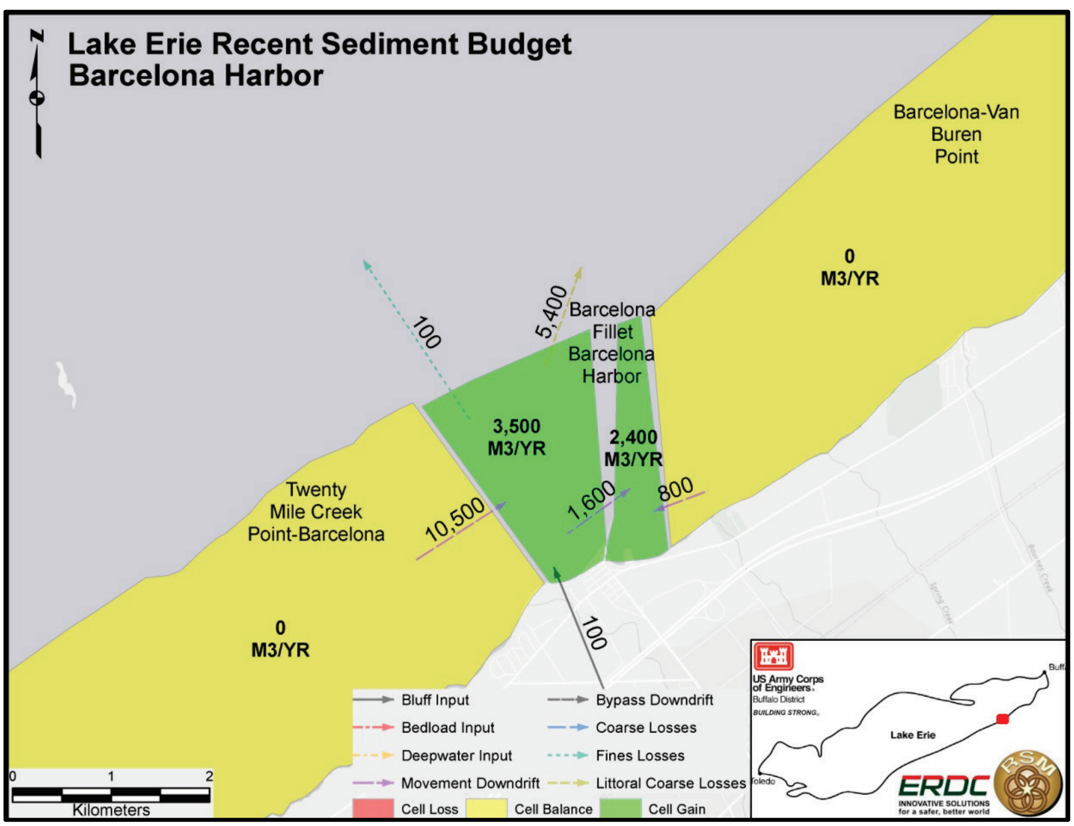
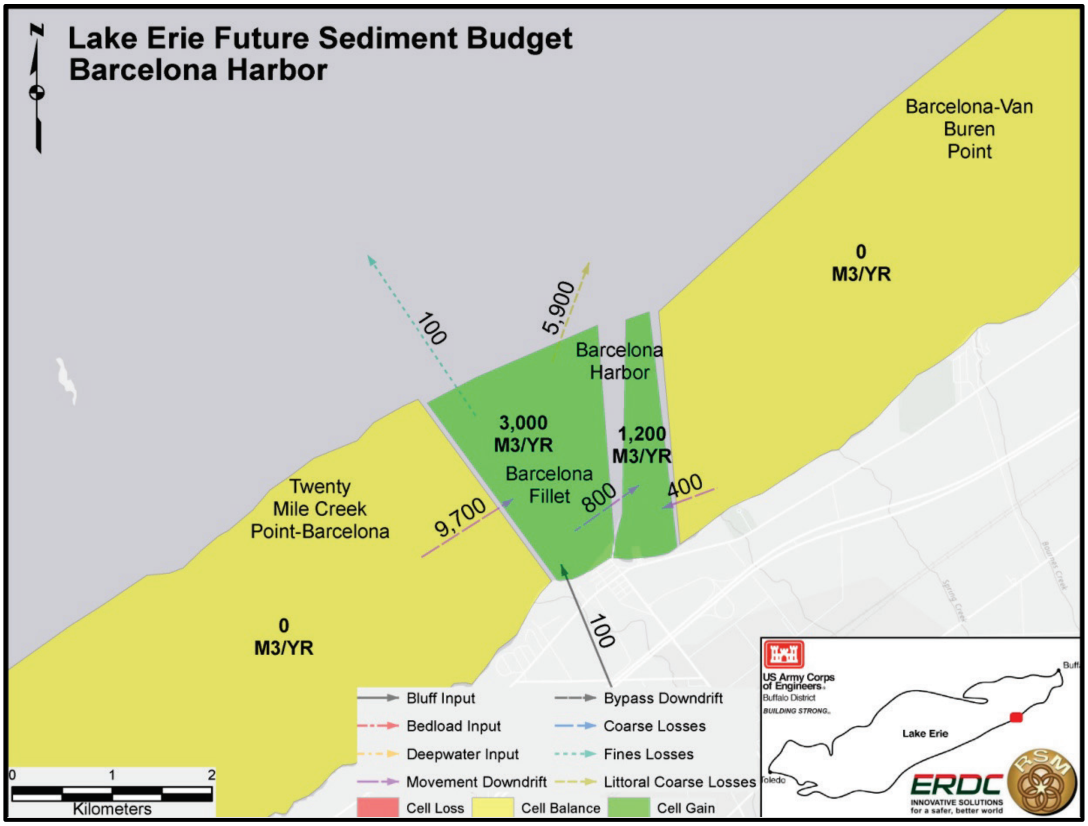


Figure 71. Barcelona Harbor Future sediment budget.



Dunkirk Harbor, NY

Dunkirk Harbor structures consist of a shore-attached West Pier (1,410 m long), a detached Outer Breakwater (860 m long), and two inner breakwaters (West, 365 m long; East, 445 m long). Breakwater construction began in 1827, and the earliest data used for sediment computation date to 1870.

To model the budget at Dunkirk Harbor, two cells were used: an outer basin cell and a harbor cell (cells 70 and 71, respectively). The outer harbor cell has been steadily eroding since the 1930s while sedimentation in the harbor increased rapidly in the Mid-Century time frame and continues in the Recent time frame at a slower rate. Because of the orientation of the harbor and the sedimentation within the harbor basin, fluxes of 4,000 m^3/year for the Mid-Century time frame and 2,000 m^3/year for the Recent and Future time frames have been added with orientation from the northeast, representing material brought in by storm events blowing out of the north-northeast. The heaviest accretion in the Mid-Century time frame took place in the east basin of the harbor, supporting the addition of this flux.

Table 26 gives predicted and measured sediment flux at Dunkirk Harbor.

Table 26. Predicted and measured volumetric change at Dunkirk Harbor (all units in cubic meters/year).

	Pre-Armoring		Mid-Century		Recent		Future
	Calculated Sediment from Bluffs	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs[1]	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs[2]	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs[2]
Outer Basin	1,500	900	-500	-700	-1,000	-900	-1,000
East/West Basins	1,300	1,800	5,400	8,700	3,400	3,300	3,400
Total	2,800	2,700	4,900	8,000	2,400	2,400	2,400
	Total Difference	-100	Total Difference	3,100	Total Difference	0	0
		-4%		39%		0%	0%

[1] Includes a flux of 4,000 m^3/year from the Northeast.

[2] Includes a flux of 2,000 m^3/year from the Northeast.

The SBAS cells for Dunkirk Harbor from the Pre-Armoring through the Future time frames are presented in Figures 72 through 75.

Figure 72. Dunkirk Harbor Pre-Armoring sediment budget.

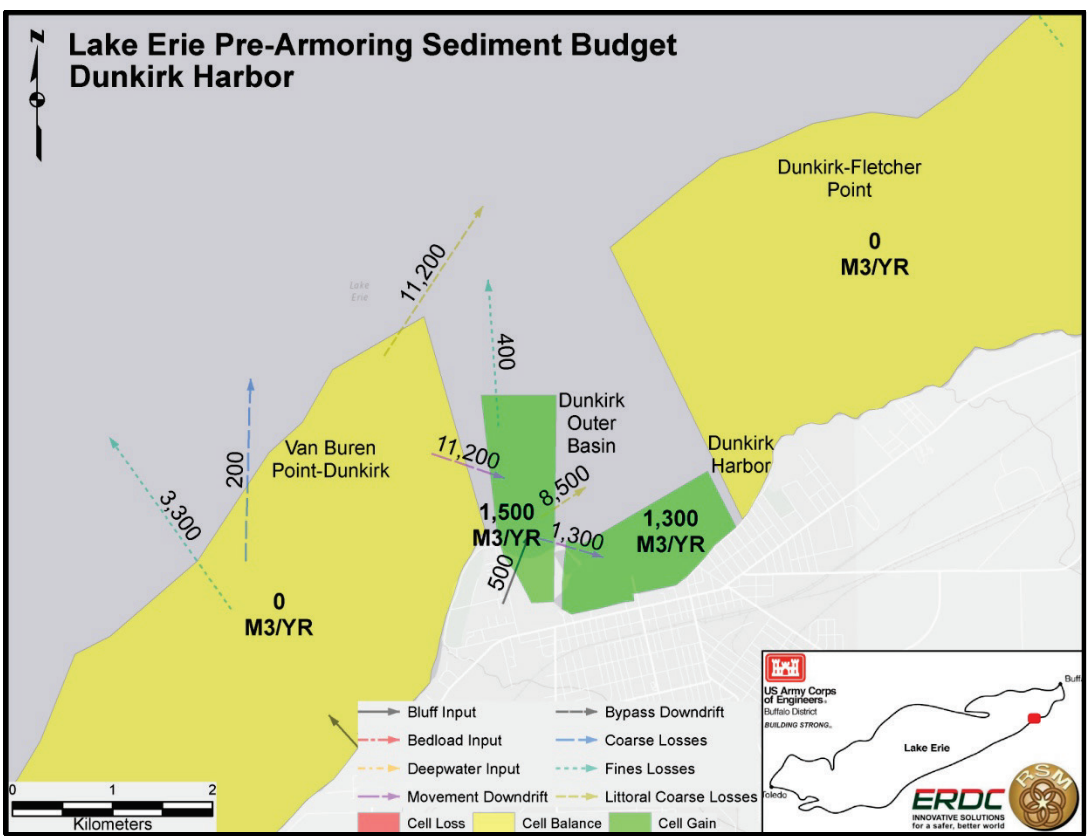


Figure 73. Dunkirk Harbor Mid-Century sediment budget.

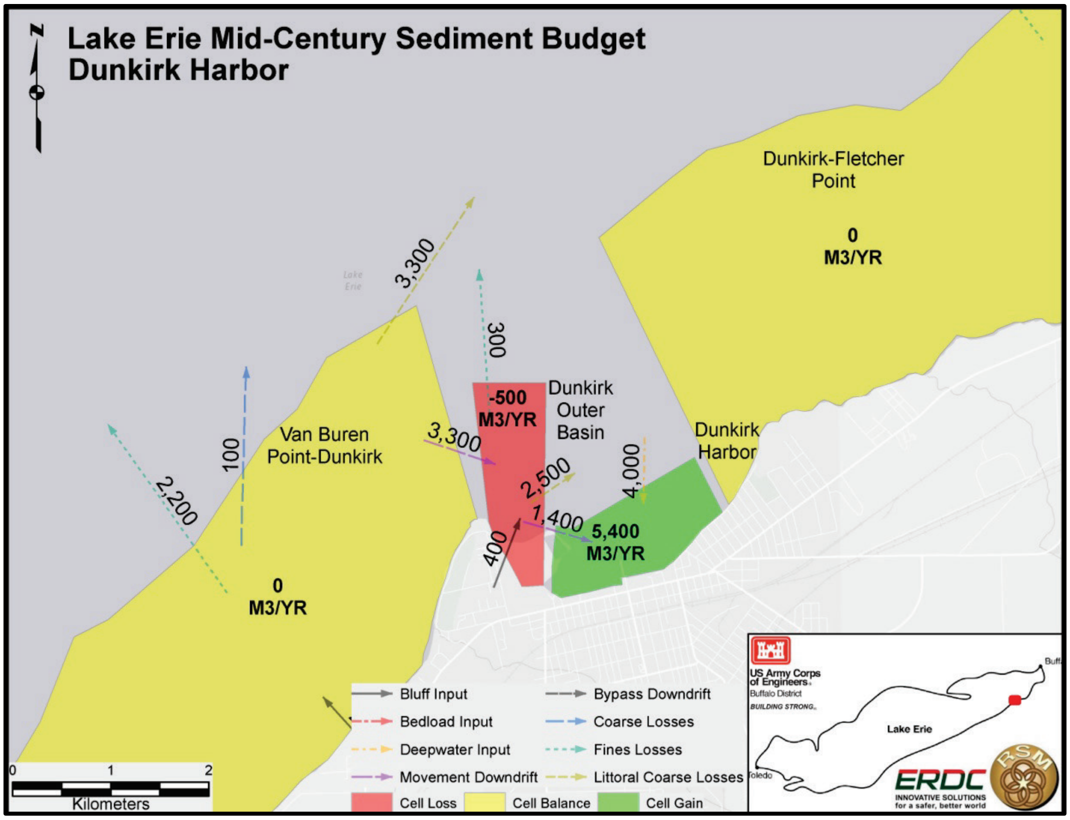


Figure 74. Dunkirk Harbor Recent sediment budget.

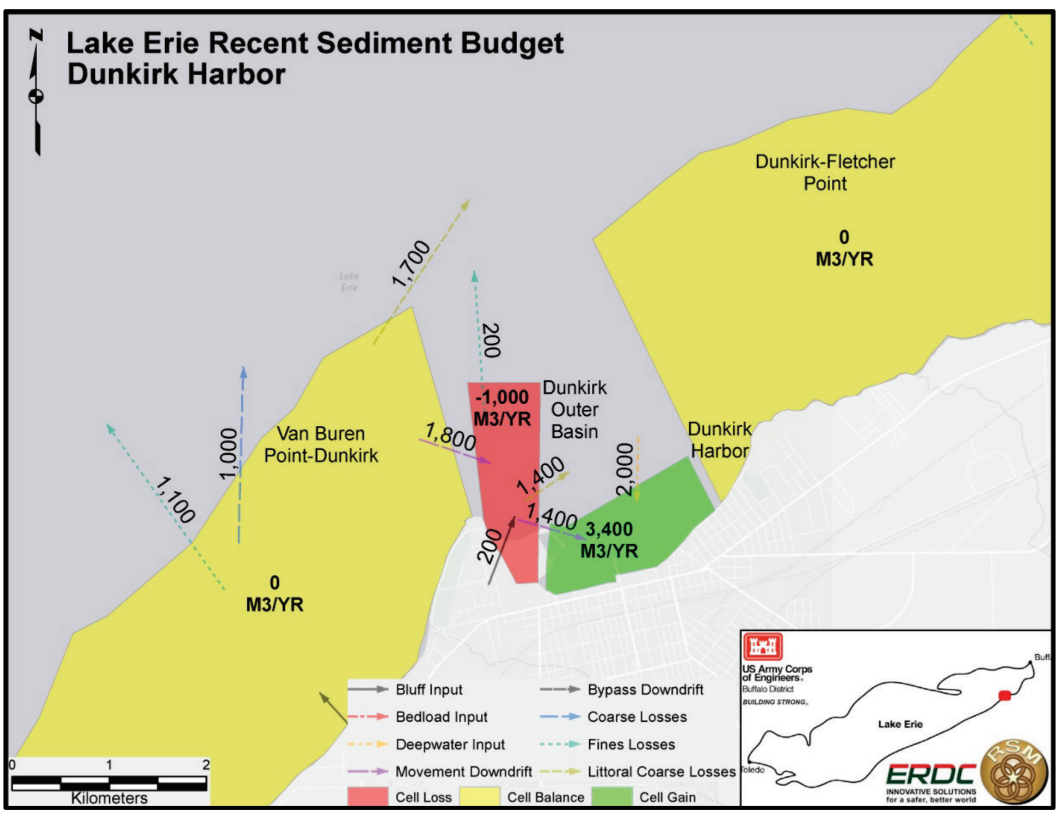
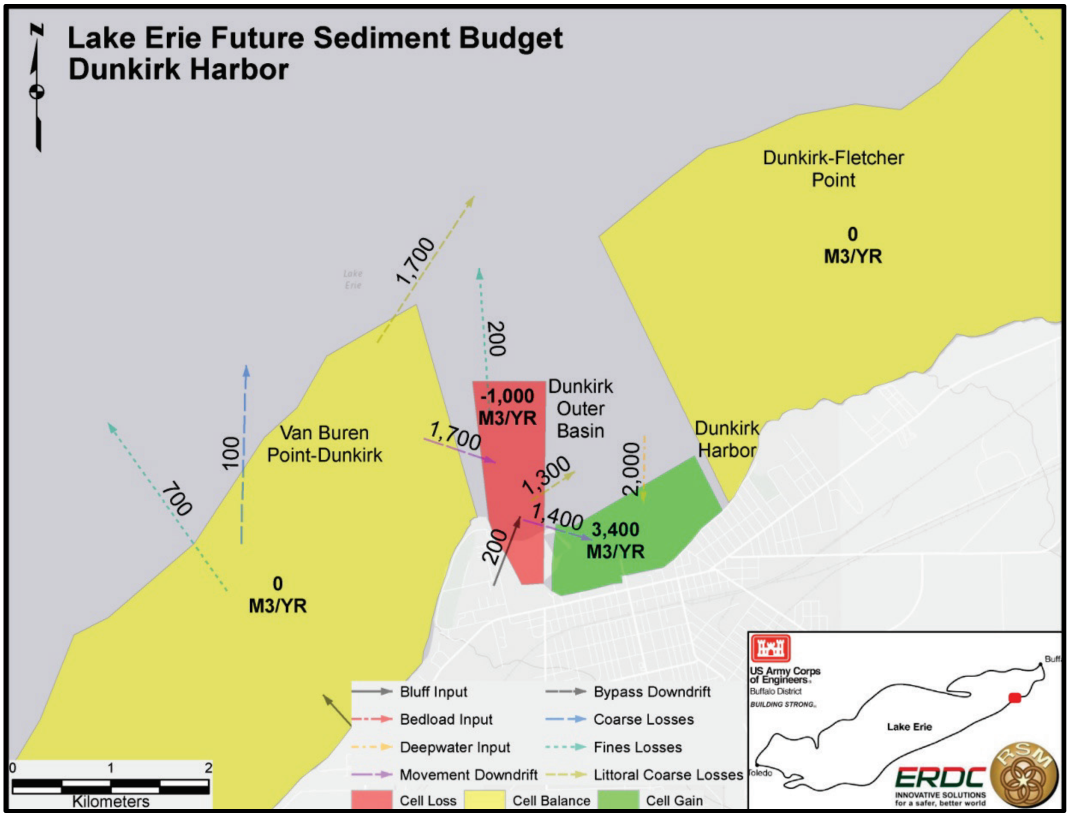


Figure 75. Dunkirk Harbor Future sediment budget.



Cattaraugus Creek Harbor, NY

Cattaraugus Creek Harbor structures consist of two arrowhead breakwaters (South, 565 m long; North, 180 m long) at the mouth of Cattaraugus Creek, completed in 1983. At Cattaraugus Creek Harbor, a bedload of 2,700 m^3/year (~3,500 yd^3) is added into the system (USACE 1976) from Cattaraugus Creek Harbor. Additionally, since completion of the project, an area of erosion has been identified off the southwestern edge of the South Breakwater. The likely cause is ice and wave scour of the original shoal at the outlet of the creek. The completion of the project shifted the locus of deposition to the north, causing the original shoal to erode.

To model the budget at Cattaraugus Creek Harbor, two separate sets of cells were used: pre-construction and post-construction. The pre-construction budget consists of two cells: a fillet cell updrift of the creek mouth and a harbor cell at the mouth of the creek (cells 75 and 76, respectively). The pocket beach updrift of Cattaraugus Creek Harbor had been stable prior to construction, so sediment passed through the fillet cell into the harbor cell. A flux of 2,700 m^3/year is added to the harbor cell to represent bed load and is passed downdrift.

The Recent and Future budgets had two additional cells modeled at Cattaraugus Creek Harbor: a scour cell and a shoal cell (cells 77 and 78, respectively). An additional flux into the shoal cell of 1,000 m^3/year is added in from erosion of the beach and near-shore down-drift of the harbor.

An average of 3,200 m^3/year has accumulated on the beach immediately south (updrift) of Cattaraugus Creek Harbor, agreeing with the predicted longshore transport rate of 4,000 m^3/year from the bluff analysis. The accretion rate in the fillet cell was modeled to be 3,200 m^3/year, with 800 m^3/year continuing downdrift. In the Future time frame, the accretion rate at the fillet is predicted to decrease to 1,000 m^3/year, with 1,900 m^3/year of LST continuing around, over, and through the South Breakwater, and 1000 m^3/year lost from the system.

During the Recent time frame, an average of 17,700 m^3/year has eroded at the location of the shoal. A new shoal has formed at the redirected mouth of Cattaraugus Creek Harbor, accreting at a rate of 7,400 m^3/year. The nearshore zone downdrift has eroded at a rate of 1,000 m^3/year, giving a net rate of change of 6,400 m^3/year between the shoal and downdrift nearshore erosion.

The erosion of the historic shoal to the southwest of the existing mouth is a result of the redirection of flow by the harbor structures, providing a temporary source of littoral material. The 2011 lidar data show the bathymetry in this area moving towards an equilibrium cross-shore profile, indicating the shape of the original shoal has gotten closer to a stable state. Because of this, the quantity of littoral material coming from this scour is projected to decrease substantially in the Future to 3,500 m^3/year in this scour cell (900 m^3/year removed from the system offshore and 2,600 m^3/year continuing into the shoal cell). As the date gets further from the construction of the project, this erosion rate will continue to decrease.

The accretion of the shoal cell in the Recent time frame is also a temporary condition. As the project matures, accretion rates in this cell will likely decrease as the project reaches equilibrium, resulting in an accretion rate of 2,000 m^3/year. Total littoral transport downdrift is expected to decrease to 4,500 m^3/year with an additional 1,500 m^3/year lost to deep water.

Other assumptions:

1. A total of 25% of the eroded material from the scour is lost from the system while the remaining 75% continues into the harbor cell and downdrift to the northeast.
2. 2,000 m^3/year of sediment is lost to deep water from the shoal in the Recent time frame, falling to 1,500 m^3/year in the Future time frame.
3. 800 m^3/year of material passes over and through the South Breakwater into the harbor cell in the Recent time frame, increasing to 1,900 m^3/year in the Future time frame as a result of the fillet reaching equilibrium.

Table 27 gives predicted and measured sediment flux values at Cattaraugus Creek Harbor.

Table 27. Measured and predicted volumetric change at Cattaraugus Creek Harbor (all units in cubic meters/year).

	Recent		Future**
	Calculated Sediment from Bluffs*	Calculated Rate from Harbor Analysis	Calculated Sediment from Bluffs*
South	3,100	3,200	1,900
North (Shoal)	6,000	6,400	2,000
Total	9,100	9,600	3,900
	Total Difference	500	5,700
		5%	59%

* Includes sediment from the Cattaraugus Creek bedload and sediment eroded from shoal.

**Accretion rates are predicted to decrease to conditions closer to preproject as a result of the project reaching a new equilibrium.

The SBAS cells for Cattaraugus Creek Harbor from the Pre-Armoring through the Future time frames are presented in Figures 76 through 79.

Figure 76. Sediment budget for Cattaraugus Creek Harbor for Pre-Armoring period.

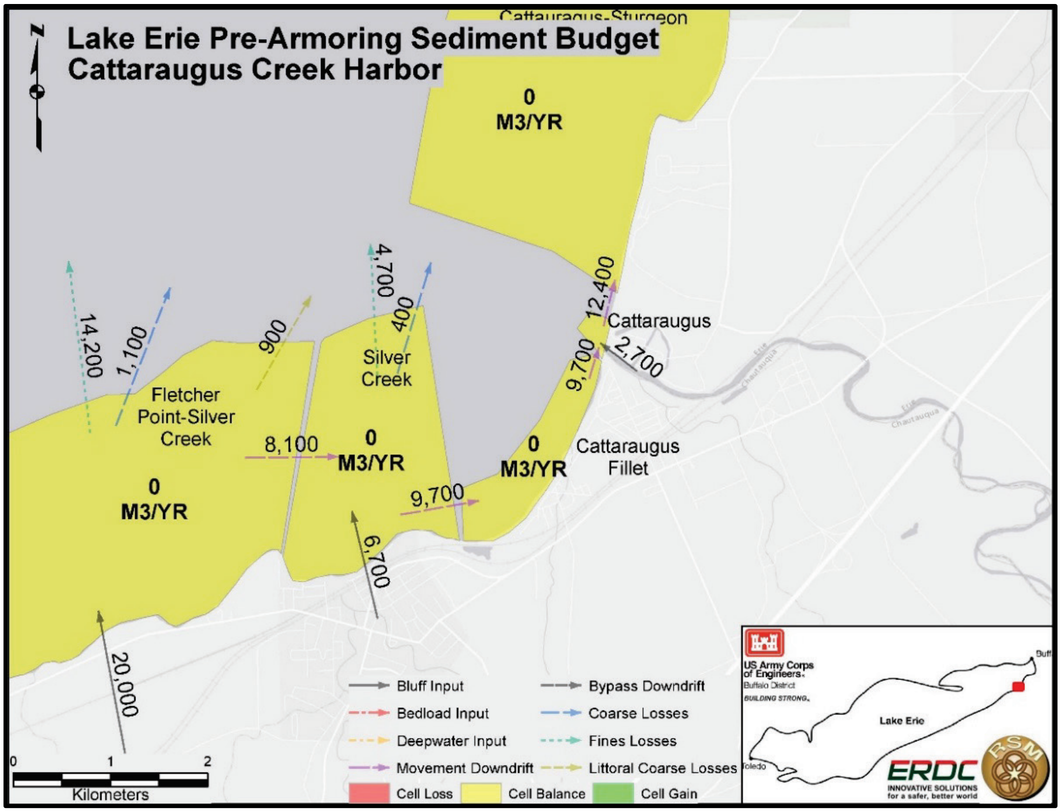


Figure 77. Sediment budget for Cattaraugus Creek Harbor for Mid-Century period.

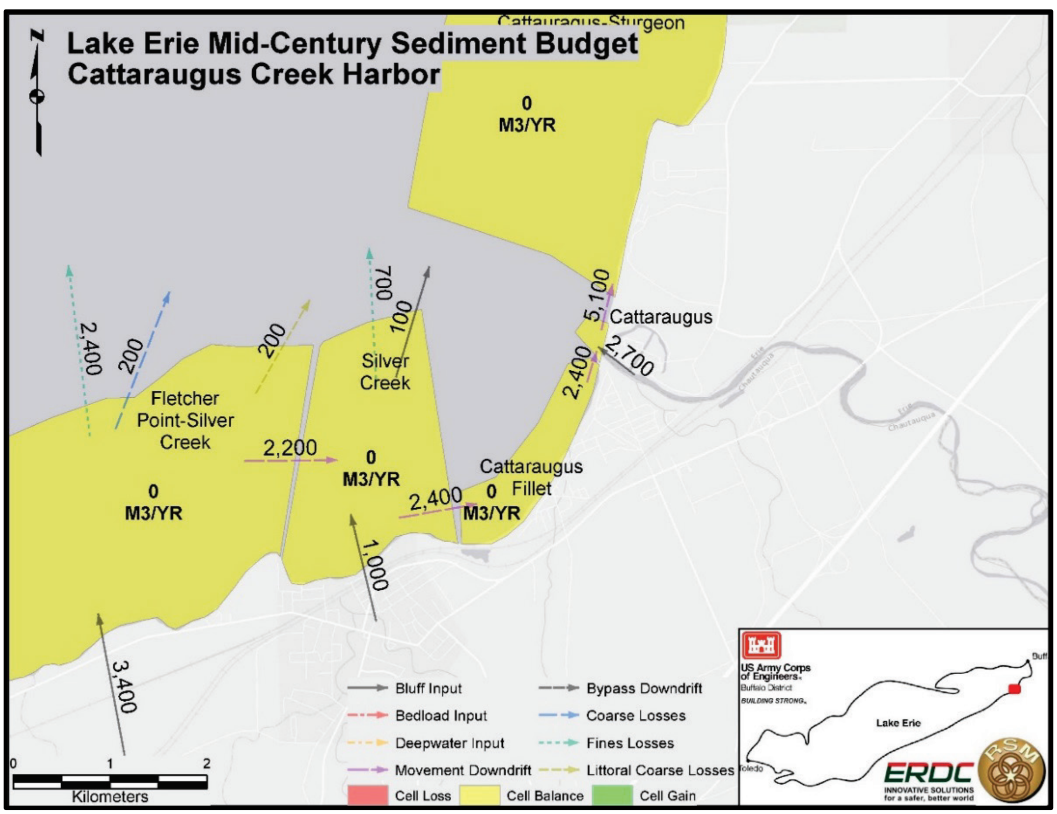


Figure 78. Sediment budget for Cattaraugus Creek Harbor for recent period.

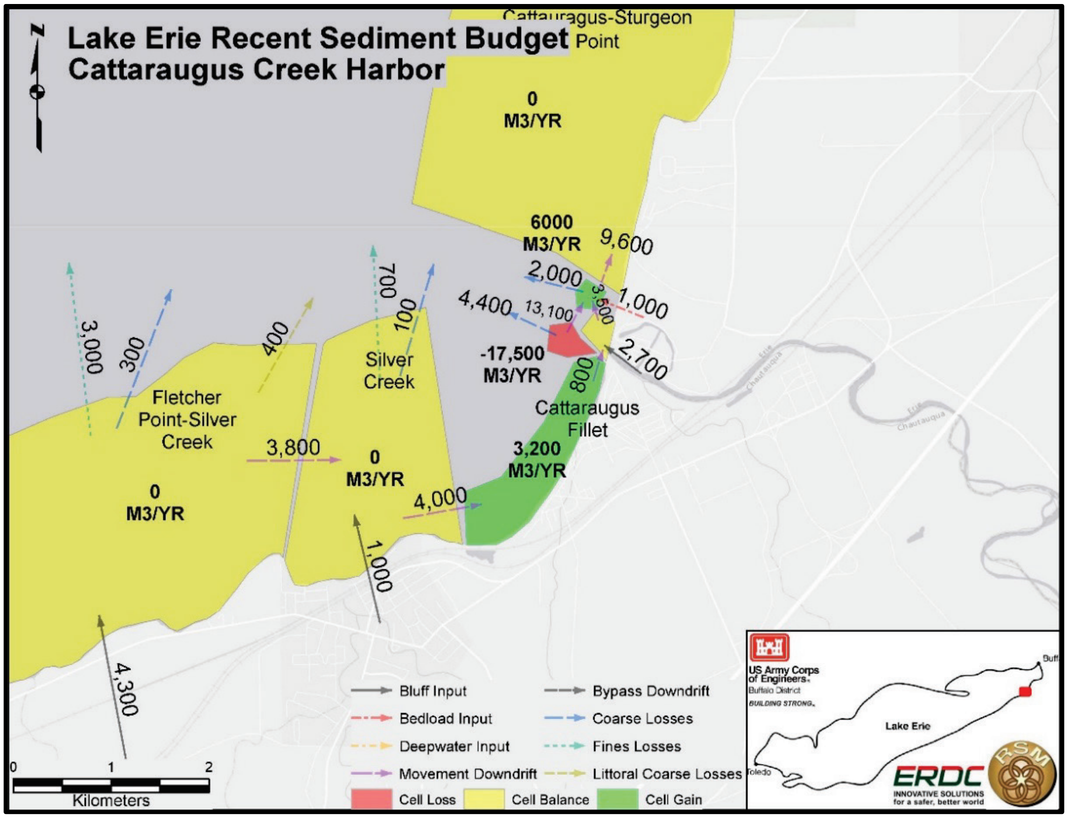
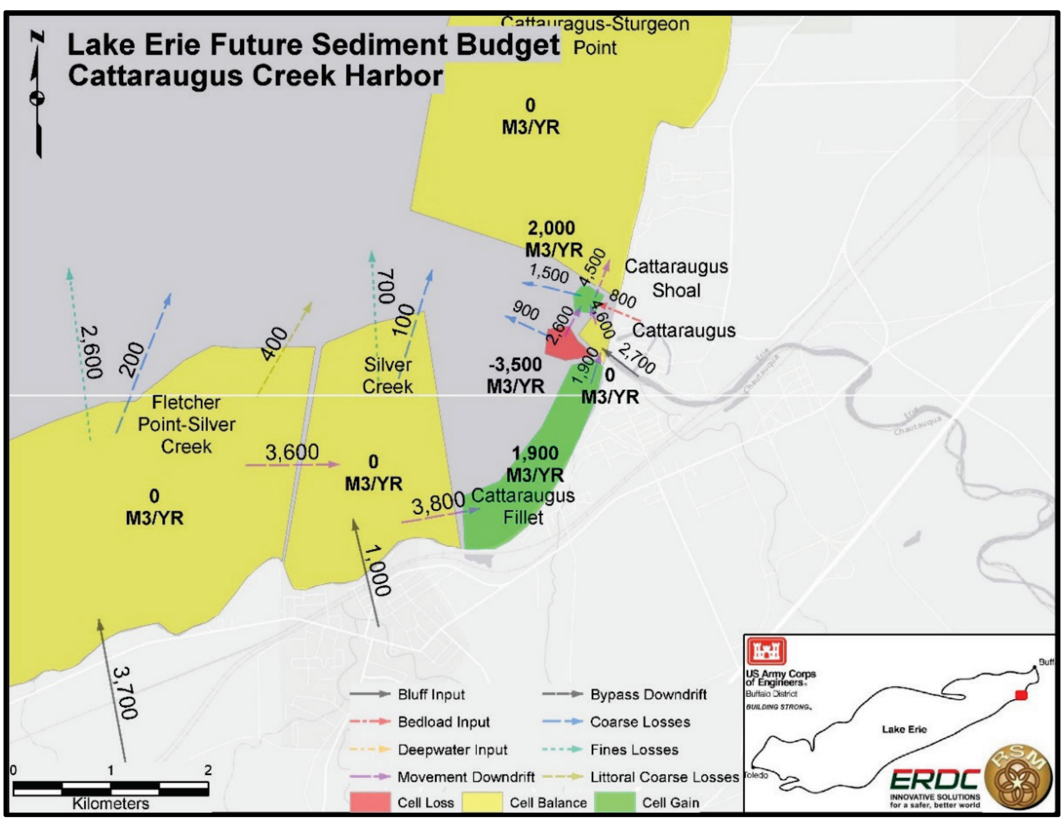


Figure 79. Sediment budget for Cattaraugus Creek Harbor for Future conditions.



10 Bypassing at Harbors/Sinks

Harbor improvements in the Great Lakes began with the earliest settlers and their attempts to maintain navigable channels for trade and safety. Large-scale improvements began in earnest in the early to mid-1800s and have continued to the present. Creek mouths were protected with piers, breakwaters provided shelter from wave action, and dredging of deep-water navigation channels further disrupted sediment transport through the littoral system.

The impact of recent shoreline improvements on the littoral system has been taken into account, and a number of harbors on Lake Erie now require sediment bypassing as part of the permitting process. These harbors provide a good case study and verification for littoral sediment quantity measurements. Knowledge of bypassing quantity is also important with regard to movement of sediments around harbors for computation of downdrift quantities.

White City Park, Cleveland, OH

White City Park is the first littoral drift impoundment east of Cleveland (Figure 80). Records provided by the Buffalo District Regulatory Branch state that up to 765 m^3/year of dredging and bypassing are authorized at this location. Actual dredging quantities are not available. Aerial imagery shows little change in shoreline position between the 1974 and 2006 images, so it is assumed that any material being trapped at this location is bypassed to the east.

Cleveland Lakefront State Park, Cleveland, OH

Cleveland Lakefront State Park lies to the east of White City Park (Figure 80). Records provided by the Buffalo District Regulatory branch state that up to 5,350 m^3/year of dredging and bypassing is authorized at this location. Actual dredging quantities are not available. A beach-fill project and series of segmented breakwaters were completed after the 1974 aerial, but additional information is not available at this time. It is assumed that any material trapped at this location is bypassed to the east.

Figure 80. White City Park (left) and Cleveland Lakefront State Park (right), Cleveland, OH. Green dots show 1 km reaches used in this study. Photograph taken 03 Feb 2012.

Eastlake Power Plant, East Lake, OH

Eastlake Power Plant is a coal-fired generating station with a water intake located along the shore. Two shore-normal jetties extend into the lake, with the inlet channel curving to the west. To maintain the inlet channel, the Plant performs annual dredging. Placement of dredged material depends on the constituency of the dredged material; finer-grained sediments are disposed offsite while coarser material is placed downdrift (east) of the facility. A breakdown of downdrift placement/offsite disposal is not available. Historical imagery shows minimal infilling of the fillet (Figure 81), so an estimated 1,000 m^3 annual accretion rate for the Mid-Century time frame, 800 m^3 annual accretion rate for the Recent time frame, and 500 m^3 annual accretion rate for the Future time frame is assumed with the remainder of the sediment bypassed to the east. Annual dredging quantities are given in Table 28.

Figure 81. Eastlake Power Plant: 1974 (left) and 2006 (right).

Table 28. Dredging Quantities at Eastlake Power Plant, 2003–2011.

Year	Volume (m^3)
2003	18,043
2004	16,056
2005	15,062
2006	0
2007	3,058
2008	5,734
2009	3,823
2010	30,582
2011	3,823
Average	10,687

Mentor Harbor, Mentor, OH

Mentor Harbor is located about half way between the Eastlake Power Plant and Fairport Harbor, OH. Dredging records between 2002 and 2011

indicate an average of 13,520 m3/year of dredging (Table 29). The shoreline has been relatively stable at this site since the 1938 imagery was flown (Figure 82). Thus, an estimated 1,000 m3/year annual accretion rate for the Mid-Century time frame, 750 m3 annual accretion rate for the Recent time frame, and 500 m3 annual accretion rate for the Future time frame is assumed, with the remainder of the sediment bypassed to the east.

Table 29. Dredging Quantities at Mentor Harbor, 2002–2011.

Year	Volume (m^3)
2002	12,997
2003	10,704
2004	19,037
2005	10,704
2006	15,903
2007	20,031
2008	15,673
2009	12,615
2010	16,897
2011	6,415
2012	7,754
Average	13,520

Figure 82. Mentor Harbor: 1936 (left) and 2006 (right).

Townline Park Marina, North Perry, OH

The marina at Townline Park in the Village of North Perry, OH, was constructed in 2009. The project included two offshore rubble-mound breakwaters, a shore-connected rubble-mound breakwater, a launch ramp, binwall structures, beach creation, and upland improvements (JJR, LLC 2010). An overview of the marina structures is displayed in Figure 83. As part of the permitting process, the Village of North Perry is required to perform regular surveys to determine sediment accumulation and bypass sand as necessary.

Figure 83. Townline Park Marina, North Perry, OH. Green dot shows study reach no. 325. Photograph 03 Feb 2012.

The first bypass event occurred in 2010, and bypassing takes place multiple times throughout the ice-free season. Annual quantities are given in Table 30. Predicted littoral volumes from bluff erosion are provided in Table 31.

Table 30. North Perry bypass volumes, 2010–2012.

Year	Volume (m^3)
2010	9,022
2011	24,026
2012	31,318
2013	24,523
2014	30,123
Average	23,802

Table 31. Predicted littoral volumes at North Perry Marina, OH.

Time Frame	Littoral Volume (m^3/year)
Pre-Armoring	26,885
Mid-Century	40,230
Recent	34,770
Future	26,645

The Future condition is based on the shore armoring that is in place now and is the most relevant condition for comparisons to the North Perry bypassing quantities. The difference in the average quantity of material bypassed and the predicted littoral volume is approximately 2,800 m^3 annually, or 11% of the predicted littoral volume. Additionally, dredging quantities have been on the rise since project completion because the town underestimated the volume of material that would need to be bypassed and has been dredging more frequently. The 2011 to 2014 dredging events are more indicative of actual accretion at the harbor.

North East Marina, Northeast, PA

North East Marina was constructed in 1991 and consists of an L-shaped concrete breakwater extending shore-normal for approximately 150 m into the lake before turning to the northeast and running shore-parallel for approximately 200 m (Morang and Melton 2001). A shore-normal breakwater on the east end of the marina provides a small entrance gap at the northeast corner of the facility (Figure 84).

Figure 84. North East Marina, North East, PA. Reach no. 143 is west of the marina. Photograph 19 Jun 2010.

Upon completion of the marina, a bypassing plan was instituted; however, regular bypassing was not initiated until 1994. Bypassing has continued from 1994 to the present. Annual bypassing totals are given in Table 32, and predicted littoral volumes are presented in Table 33.

Table 32. Bypass quantities at North East Marina, 1993–2010 (based on Morang and Melton [2001] with more recent data from Pennsylvania Fish and Boat Commission).

Year	Volume (m^3)	Year	Volume (m^3)
1994	10,824	2003	7,920
1995	13,552	2004	9,649
1996	15,948	2005	11,572
1997	9,987	2006	11,747
1998	18,133	2007	13,403
1999	11,672	2008	13,199
2000	15,809	2009	14,516
2001	10,126	2010	17,391
2002	5,821	Average	12,428

Table 33. Predicted littoral volumes at North East Marina, PA.

Time Frame	Littoral Volume (m^3/year)
Pre-Armoring	36,200
Mid-Century	32,500
Recent	25,500
Future	21,900

As the Future condition is based on the shore armoring that is in place now, this is the most relevant condition for comparisons to the North East Marina bypassing quantity. The difference in the average quantity of material bypassed and the predicted littoral volume is approximately 9,400 m^3/year, or 43% of the predicted littoral volume. This discrepancy may be partially explained due to the small fillet building up to the west of the harbor, primarily in the area beyond the marina property. Additionally, a majority of the littoral sediment in this area is derived from the erosion of till, which leads to uncertainty in the coarse fraction entering the system from bluff erosion. Also, some sediment that is not quantified may be lost offshore due to redirection around the breakwater.

Sturgeon Point Marina, Evans, NY

Sturgeon Point Marina was constructed in 1988 and consists of a 285 m long West Breakwater extending from shore and a smaller 105 m long East Breakwater (Figure 85). The design documents for the marina predicted an annual bypassing quantity from the updrift fillet of 6,190 m^3 and dredging of approximately 2,295 m^3 every 5 years from within the harbor (USACE 1987).

Since completion of the marina, actual accretion volumes have been higher than predicted. Dredging records indicate a rate of 7,645 m^3 annually bypassed from the updrift fillet and 5,350 m^3 annually dredged from within the marina (USACE 2004), or a total of 12,995 m^3 annually.

Figure 85. Sturgeon Point Marina, NY. Shale platforms can be seen through the water offshore of the marina. Photograph 25 Sep 2013.

Sediment profiles obtained prior to the construction of the project indicated a high quantity of shale plates within the beach sediments (Figure 86). Soft shales are the dominant bedrock in this region and contribute a large volume to the littoral system. Once eroded from the bedrock, the shale quickly degrades mechanically to finer particles and eventually is lost from the system. There is a short period, however, when the shale makes an important volumetric contribution to the littoral system. Due to the high quantity of shale plates and the short reach between Cattaraugus Creek and Sturgeon Point (approximately 16 km), the shale coarse fraction contribution to the system was increased to between 30% to 50%, with the percentage increasing closer to Sturgeon Point. Predicted littoral volumes at Sturgeon Point due to bluff erosion/bedload from Cattaraugus Creek are given in Table 34.

Figure 86. Excavation in west fillet at Sturgeon Point pre-project construction (16 Nov 1988). Photograph shows high quantity of shale plates in soil column (USACE 2004).

Table 34. Littoral volumes at Sturgeon Point.

Timeframe	Littoral Volume (m^3/year)
Pre-Armoring	36,400
Mid-century	10,000
Recent	12,700
Future	7,100
Difference:	-300
	-4%

The predicted littoral volume in the Recent time frame underpredicts the measured littoral volume dredged at Sturgeon Point by 300 m^3/year, or 4%. The Recent time frame is used as the basis for comparison at Sturgeon Point due to the high sediment load supplied to the littoral system by the eroding historic shoal at Cattaraugus Creek.

The predicted littoral system at Cattaraugus contributes an additional 6,900 m^3/year to the LST rate above the amount predicted in USACE (1987). This increase is due to erosion of the historic shoal and deposition at

the new shoal, as discussed in Section 8. USACE (1987) also underpredicted the LST rate at Sturgeon Point by 6,500 m^3/year, indicating that the bluff analysis in the Sturgeon Point Design Document was accurate but the movement of the shoal at Cattaraugus Creek was not predicted. With the historic shoal at Cattaraugus Creek nearly depleted, dredging at Sturgeon Point is expected to decline significantly in the future.

11 Discussion

Overview

Sediment budgets are of increasing value given the ever-greater pressures to manage the lake shoreline with greatly restricted Operations and Maintenance funding. The sediment budget presented here is the most comprehensive attempt yet to compute a budget for the U.S. shoreline of Lake Erie.

This study utilized bluff erosion as the primary driver for sediment inputs into the system, with offshore losses and trapping at Federal harbors as the primary sediment sinks. Historical data were derived from historic charts, dredging records, previous sediment studies, and first-hand experience with the natural processes on Lake Erie.

The bluff erosion measurements could be matched well with harbor accretion or sediment bypassing measurements at most points along the shoreline. However, bluff erosion measurements underpredicted measured sediment volumes at Fairport Harbor by 45% for the Pre-Armoring era, 74% for the Mid-Century period, and 8% for the Recent period (Table 20).

Future data/analysis needs

Shale contribution to the littoral system

A major source of uncertainty in this study is the determination of littoral material contributed by the weathering and erosion of shale bluffs. Shale accounts for the majority of the sediment entering the system in Erie and Chautauqua Counties in New York as well as the western section of Cuyahoga County, OH. Shale also contributes between 25% and 44% of the total sediment influx in Lorain County, OH (Table 35).

A high quantity of shale plates were observed in samples obtained prior to construction of the Sturgeon Point Marina (Figure 86), and field observation in many areas along the New York shoreline verify a significant quantity of eroded/weathered shale on the beaches and in the immediate littoral system. What is unknown is the spatial and temporal scale of the eroded shale as it pertains to the littoral volume. The material

degrades mechanically to very fine particles that can be winnowed out of the littoral system, so the contributions to the littoral system must decrease further from the source. However, the rate at which degradation occurs is unknown. The method of littoral volume determination would benefit greatly from a combined field/laboratory investigation into the process from which shale is weathered, eroded, mechanically degraded, and finally removed from the system as fines.

Measurement of short term adjustment to LST direction

The sediment fluxes represented in this budget reflect long-term littoral transport trends and do not account for short-term storm events and temporary transport direction reversals. The nodal points in central Ohio shift seasonally in response to prevailing wind and wave direction[1]. The nodal point at Avon Lake is thought to shift seasonally between Vermilion and Cleveland (a distance of approximately 55 km).

A detailed study in the Vermilion-to-Cleveland reach would be beneficial for understanding the short-term, storm-induced transport.

Till contribution to the littoral system

Till has a highly variable constituency due to its depositional environment. The coarse fraction of till layers can vary dramatically both along a section as well as vertically through the section. A few studies have measured the gradation of the till at various locations along the lake shore (Carter 1977; Knuth 2001). The Buffalo District acquired core samples along the eastern Pennsylvania shore in 1986, but a comprehensive measurement of the constituency of the till throughout the study area would greatly increase the confidence associated with the results of this present study. Multiple samples at each representative location would be necessary to determine an accurate gradation for the till bluffs.

[1] Donald Guy, ODNR, Division of Geological Survey (retired), personal communication, 29 April 2013.

Table 35. Bluff erosion rates by county.

	Total Shale Volume Eroded (m^3/year)				Total Bluff Volume Eroded (m^3/year)				Percentage of Bluff Volume from Shale Contribution			
	Pre-Armoring	Mid-Century	Recent	Future	Pre-Armoring	Mid-Century	Recent	Future	Pre-Armoring	Mid-Century	Recent	Future
Erie County, OH	800	400	400	400	51,000	48,300	52,300	42,600	2%	1%	1%	1%
Lorain County, OH	20,900	9,000	9,400	4,400	84,900	29,600	21,300	10,000	25%	30%	44%	44%
Cuyahoga County, OH-West of Cleveland	54,700	25,200	14,900	11,800	74,700	33,000	20,100	14,300	73%	76%	74%	83%
Cuyahoga County, OH-East of Cleveland	600	500	400	200	29,300	21,700	8,100	5,100	2%	2%	5%	4%
Lake County, OH	0	0	0	0	296,600	306,500	237,200	168,000	0%	0%	0%	0%
Ashtabula County, OH	400	400	700	700	216,800	147,700	246,800	202,100	0%	0%	0%	0%
PA West of Presque Isle	0	0	0	0	226,200	268,200	163,100	148,500	0%	0%	0%	0%
PA East of Presque Isle	28000	18200	16700	15300	294700	248200	198300	177700	10%	7%	8%	9%
Chautauqua County, NY	123,700	29,600	36,600	35,400	248,500	65,500	72,100	68,900	50%	45%	51%	51%
Erie County, NY	67,200	27,200	13,400	10,900	109,500	37,800	20,300	15,000	61%	72%	66%	73%

Bedload contribution from tributaries

Cattaraugus Creek is the largest contributor of material to the littoral system along the New York lakeshore and for the purposes of this study, was modeled as the only contributor. The majority of sediment load carried by tributaries to Lake Erie is fine grain. Coarse material from the small and intermediate basins can only be expected during high flow events (Buxton 1977).

Processes around Port Clinton sink

The area around Port Clinton is considered as a sink for material coming from both the east and the west. The harbor analysis at Port Clinton did not show large quantities of material accreting, indicating that material is being lost offshore. A more detailed set of surveys at Port Clinton, as well as study into the wave mechanisms present in this area, would help to define the littoral processes.

Ice rafting and loss offshore

Transport of beach and possibly till material offshore as a result of entrainment in ice needs to be further investigated with field studies. It is unknown how much material is carried away from shore and under what circumstances. The results of field studies conducted by Barnes et al. (1993) at Lake Michigan may not be applicable to Lake Erie because of different geology and oceanographic conditions.

12 Conclusions

To calculate a sediment budget, the U.S. shoreline of Lake Erie from Maumee Bay, OH, to Buffalo, NY, was divided into 82 littoral cells. The cells vary in size from multi-kilometer stretches of bluff coast to individual harbors only a few hundred meters wide. Sediment budgets for four periods have been computed:

1. Pre-Armoring (1860s to late-1930s): representing the early development era
2. Mid-Century (late-1930s to late-1970s): representing the mid-twentieth century era of active harbor dredging, but comparatively limited shore protection
3. Recent (late 1970s to 2006-2009): era of extensive suburban development and shore armoring
4. Future: projected sediment inputs and longshore transport.

The budgets were based on computing sediment input into and determining losses from the littoral system. Most of the input along this shore is derived from bluff recession or (west of the Marblehead Peninsula, OH) erosion of low lacustrine deposits. Bluff recession was based on measuring bluff edges on historical maps or geo-referenced aerial photographs. To determine losses, volumes of sand stored in harbor fillets were computed using historical USACE bathymetry charts and historical dredging data. Future sediment budget predictions were based on the bluff recession rates from the Recent time frame (1970s–early 2000s) but with the input volume reduced because of the extensive shoreline armoring that now protects large portions of the coast. Ohio, in particular, is extensively armored.

Uncertainty in the computed sediment budget stems from numerous sources. First, shoreline (or bluff line) definition and detection is not a precise art. Most low shorelines are defined based on water-derived datums such as tide lines. For cliff or bluff-bound water bodies, the bluff edge is often used as a surrogate for the "shoreline" (Boak and Turner 2005). For low shorelines, such as those in western Ohio, potentially one of the most significant sources of error can be the assumption that the feature recorded at one instant in time (i.e., when a photograph was taken

or lidar survey flown) represents a *normal* or *average* condition. The researcher using archival material has little choice but to use whatever materials are available. With bluff edge detection, the bluff is more stable than a water-edge feature and does represent a more average condition. However, as documented above, interpretation is difficult in locations where the bluff edge is obscured by trees, poor lighting conditions, or urban overlay.

Second, the stratigraphy of the Lake Erie bluffs is not precisely known kilometer by kilometer. In this report, the proportion of till versus bedrock versus lacustrine material was interpreted from stratigraphic cross sections, but these were interpretations based on surveys and field notes from various field workers. Ideally, a new stratigraphic survey would have been conducted, but this would have entailed a significant cost and time burden. Even continuous photographic coverage of the shore is of limited value because of features that obscure the underlying sediment (trees and vegetation, urban construction) and because of the difficulty in scaling geology on oblique photography.

Third, the percentage of coarse versus fine grain sediment in the till along the lakeshore varies greatly. These data need better definition. A field-sampling program would be very beneficial.

Fourth, there is inherent uncertainty in the measurement of sediment accumulation at the harbor structures. Uncertainty results from potential cartographic errors in the initial mapping (in many cases in the mid-1800s), varying degrees of accuracy of data, limits in data sources, and generalization of topographic features as a result of the 3D mapping.

Potential sources of error have been minimized to a great extent but will always exist with historic data. Future projections could be refined and errors reduced with the addition of future high-resolution data sets used for computation. Some repeated high-resolution data sets are becoming available via lidar overflights. However, recent data collection was conducted when the study area was subject to high suspended sediment loads as well as algal blooms, thus limiting the ability of the sensor to capture bathymetric data. The Buffalo District has collected high-resolution bathymetry at Federal harbors, but these data sets are generally limited to dredged areas in the Federal channel and are of little use to this study. Dredging quantities were also investigated, but the constituency and the sources of the material (riverine vs. littoral) are unknown and of little use in determining littoral volumes.

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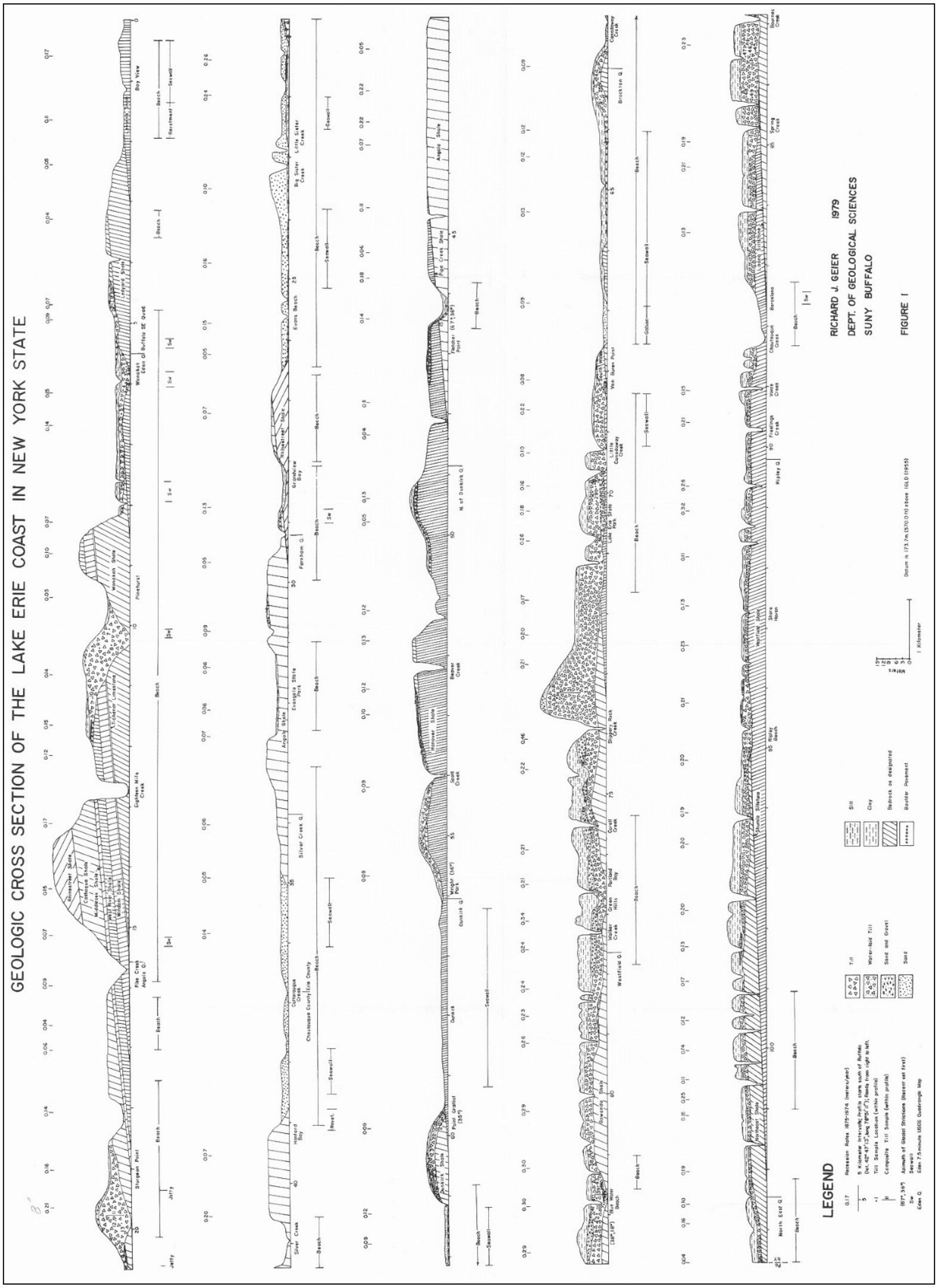
Appendix A: Bluff Stratigraphy – New York and Ohio

Figure A-1, from Geier and Calkin (1983), is a cross section of the stratigraphy of the coastal bluffs of Lake Erie in New York State. This is similar to a view that a person would see cruising parallel to the shoreline on a boat. The origin of this plot may be Geier's M.A. thesis (Geier 1983). Similar cross sections were not available for Pennsylvania.

For the Ohio shoreline, the ODNR supplied cross sections from published reports and unpublished manuscripts (Figures A-2 and A-3).

Figure A-1. New York shore stratigraphy (from Geier and Calkin 1983).



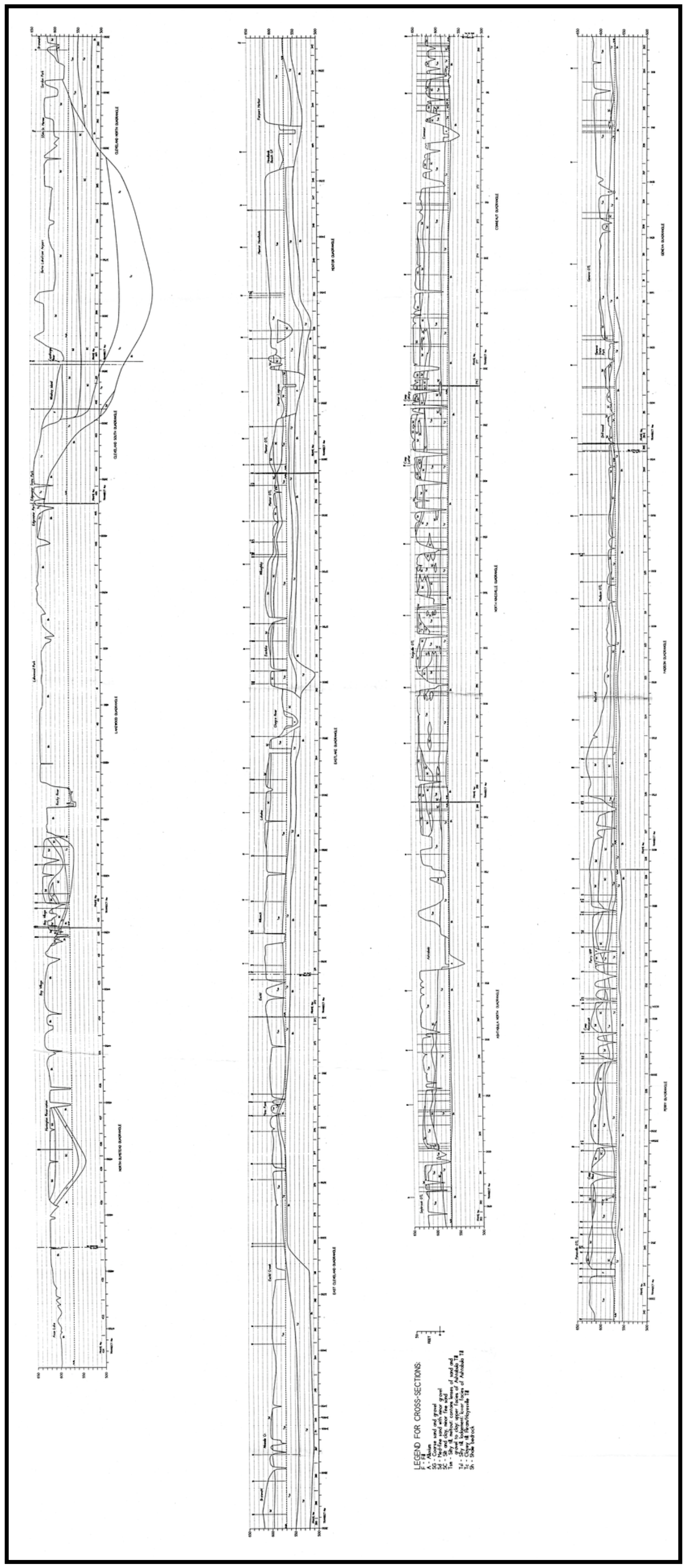


Figure A-2. Cross sections of eastern Ohio bluffs (after Stone et al.[1]). The Cleveland urban area with its armored coast is not shown.

[1]Stone, B. D., R. R. Pavey, J. A. Fuller, and D. S. Foster. Unpublished report. Map of surficial surface materials in the Lake Erie coastal area, northeastern Ohio. U.S. Geological Survey Open-File Report. Denver, CO: U.S. Geological Survey Publications Warehouse.

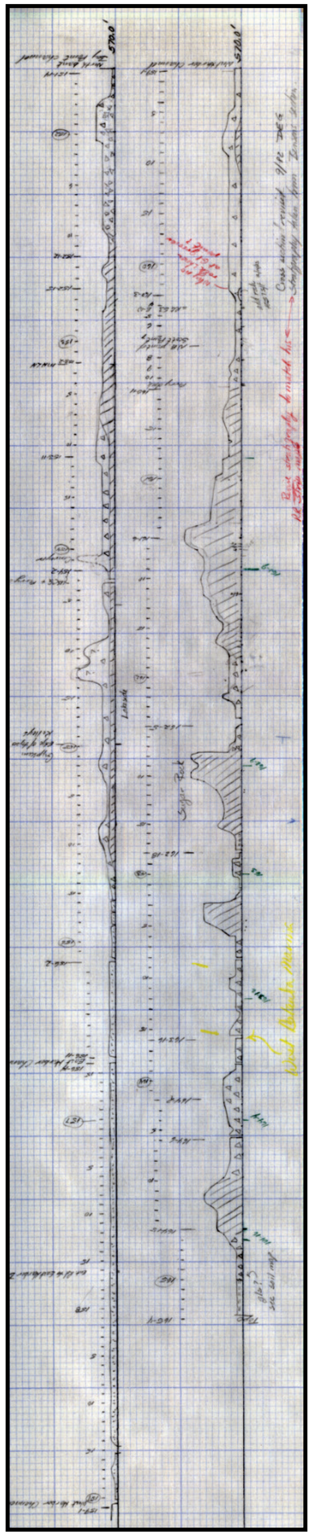


Figure A-3. Cross sections from Ottawa-Lucas counties (provided by ODNR). Contrast enhanced from original scan using Photoshop Elements software version 8.

Appendix B: Complete Lake Erie Sediment Budget

The following figures (Figures B-1 through B-60) show the sediment budgets for the four time periods (a) Pre-Armoring, (b) Mid-Century, (c) Recent, and (d) Future along the southern Lake Erie shoreline of the United States. The figures begin at Maumee Bay at the west end of Lake Erie (just west of Toledo Harbor, OH) and proceed eastward to the Sturgeon Point/Buffalo, NY, region.

Figure B-1. Toledo to Locust Point Pre-Armoring sediment budget.

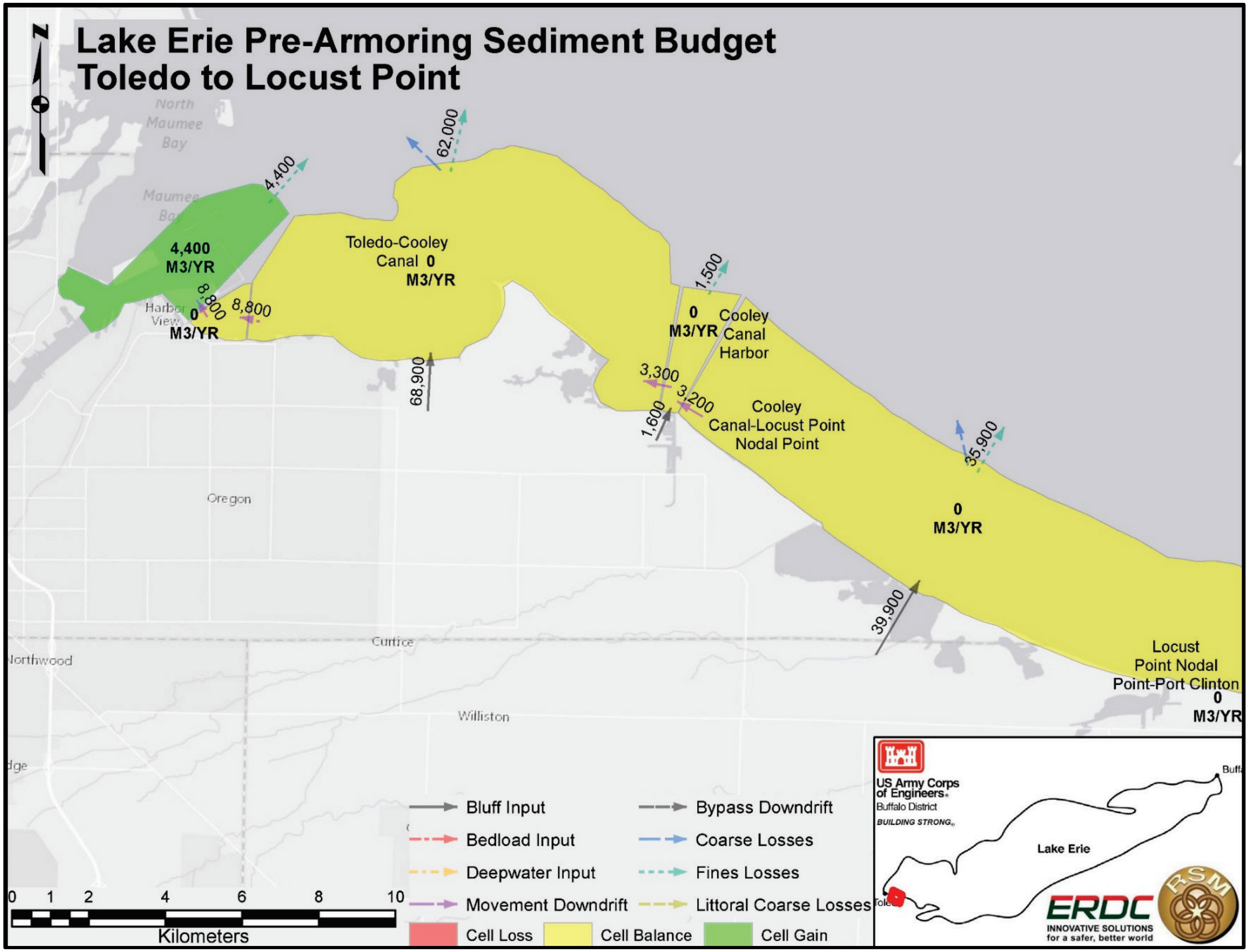


Figure B-2. Toledo to Locust Point Mid-Century sediment budget.

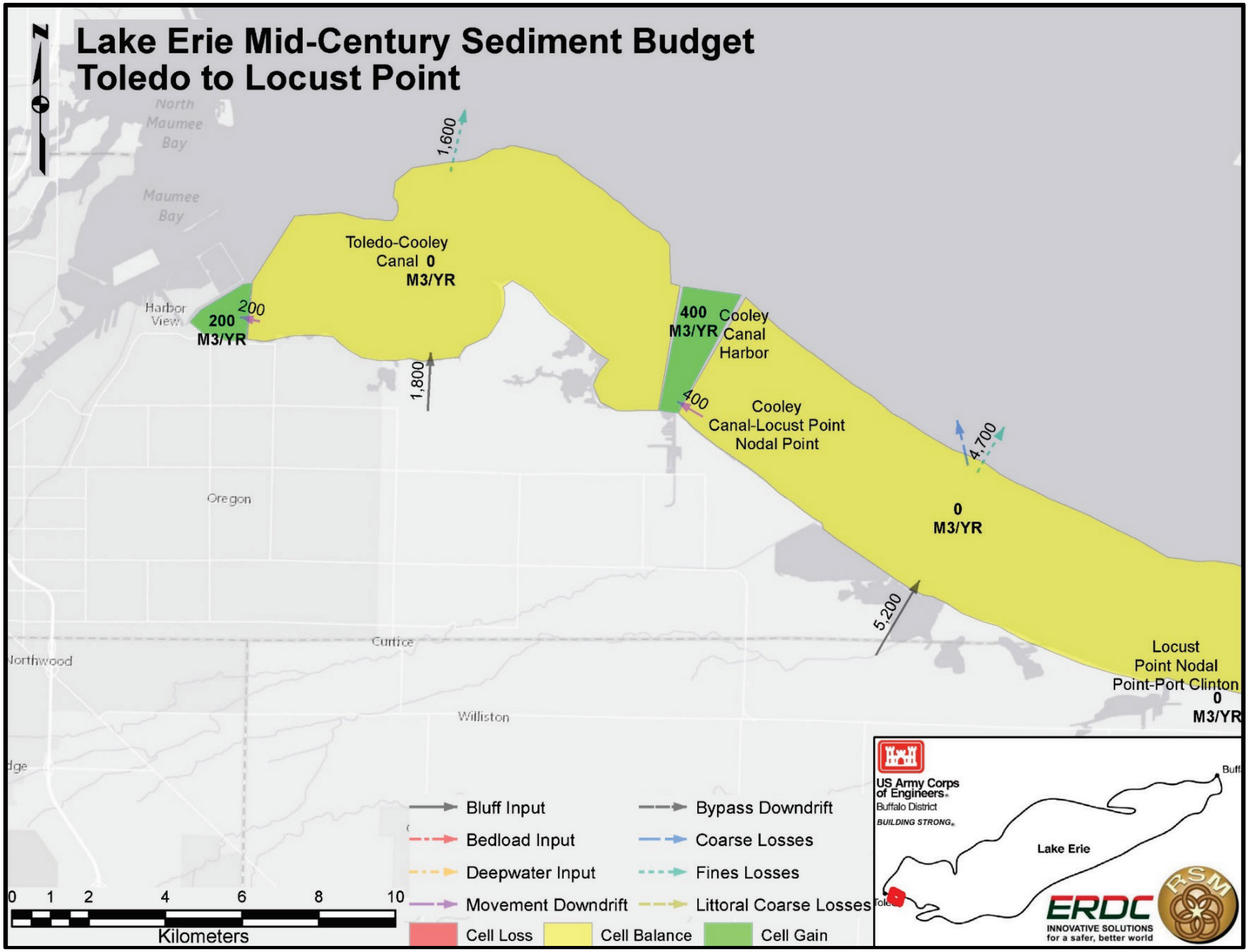


Figure B-3. Toledo to Locust Point Recent sediment budget.

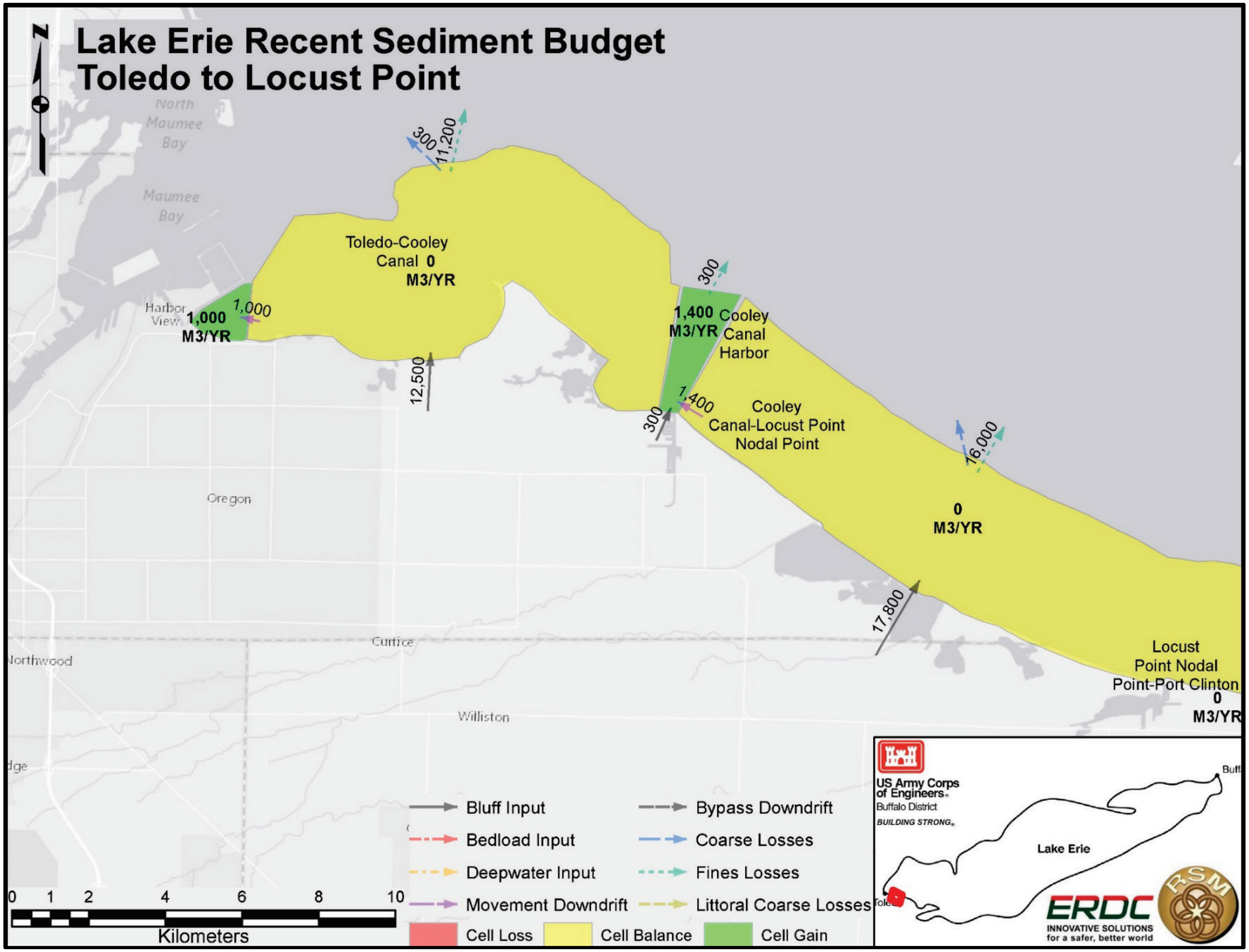


Figure B-4. Toledo to Locust Point Future sediment budget.

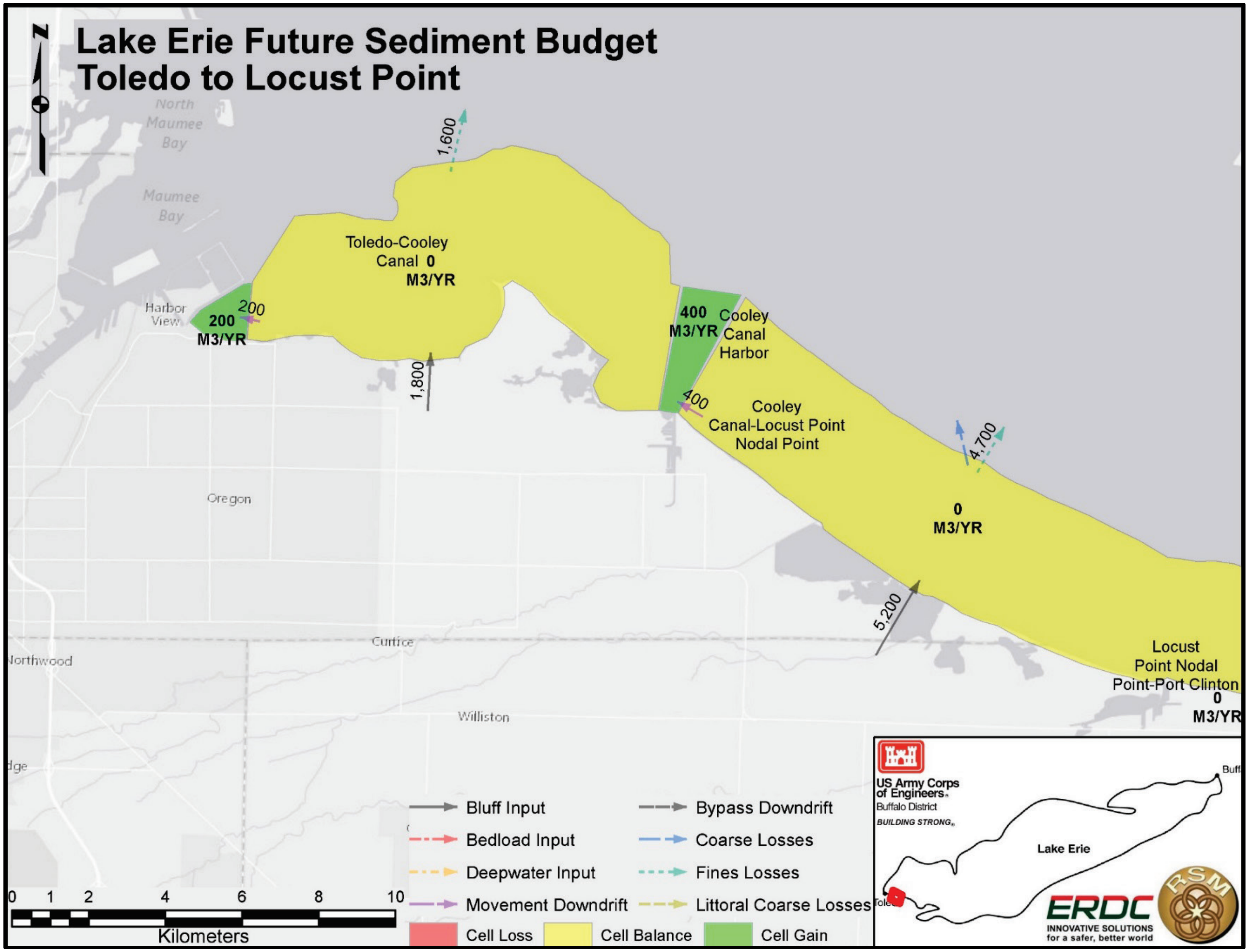


Figure B-5. Locust Point to Sandusky Pre-Armoring sediment budget.

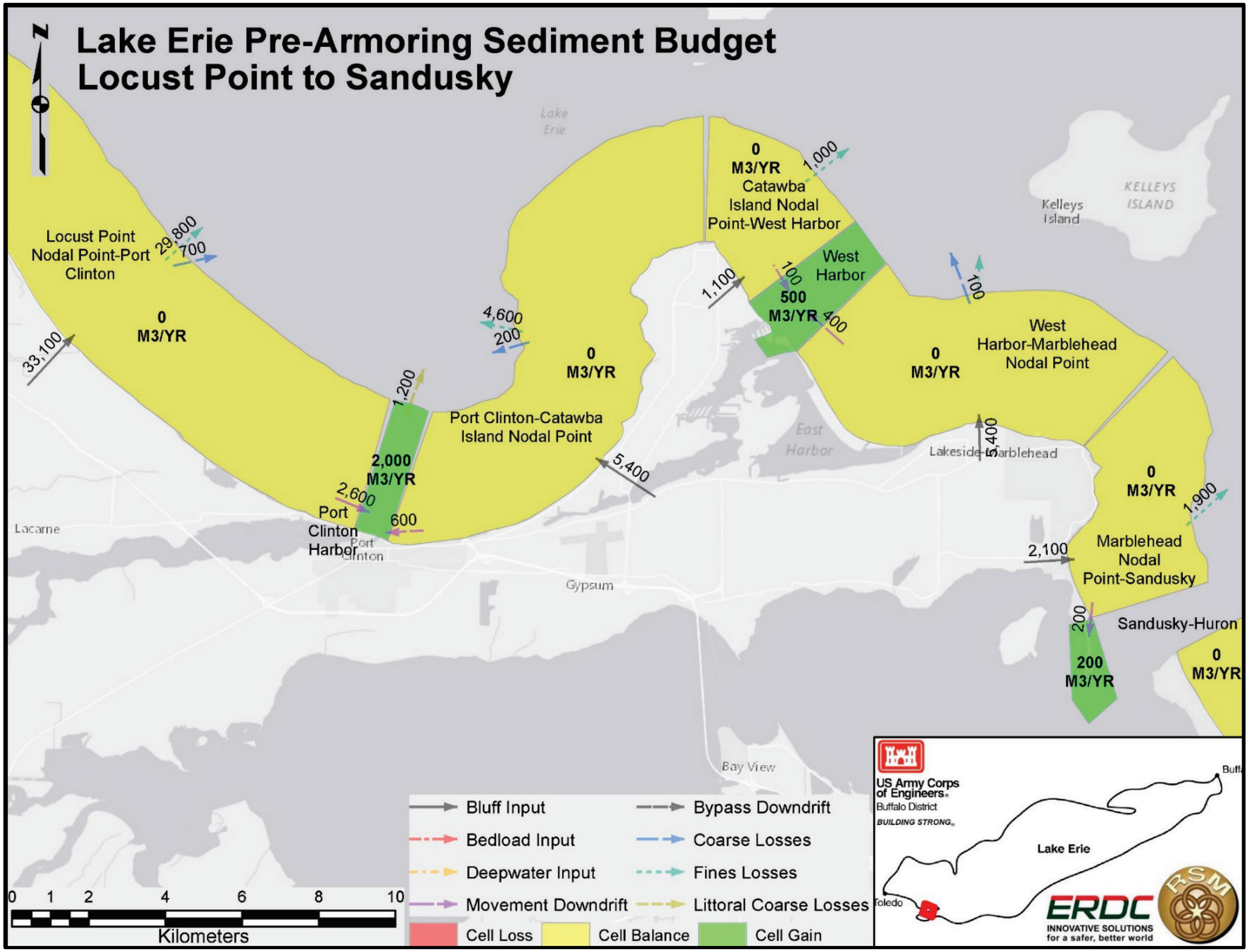


Figure B-6. Locust Point to Sandusky Mid-Century sediment budget.

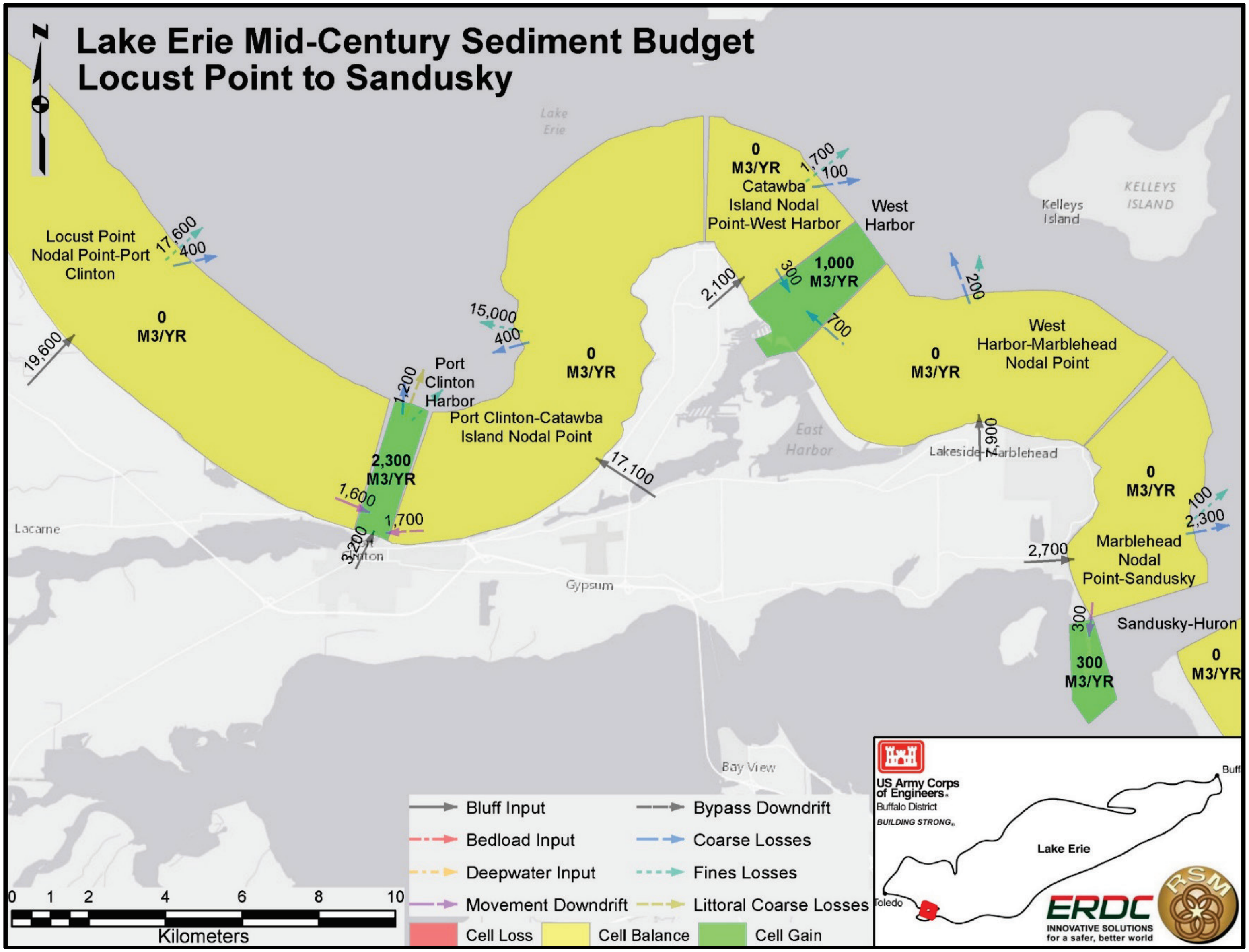


Figure B-7. Locust Point to Sandusky Recent sediment budget.

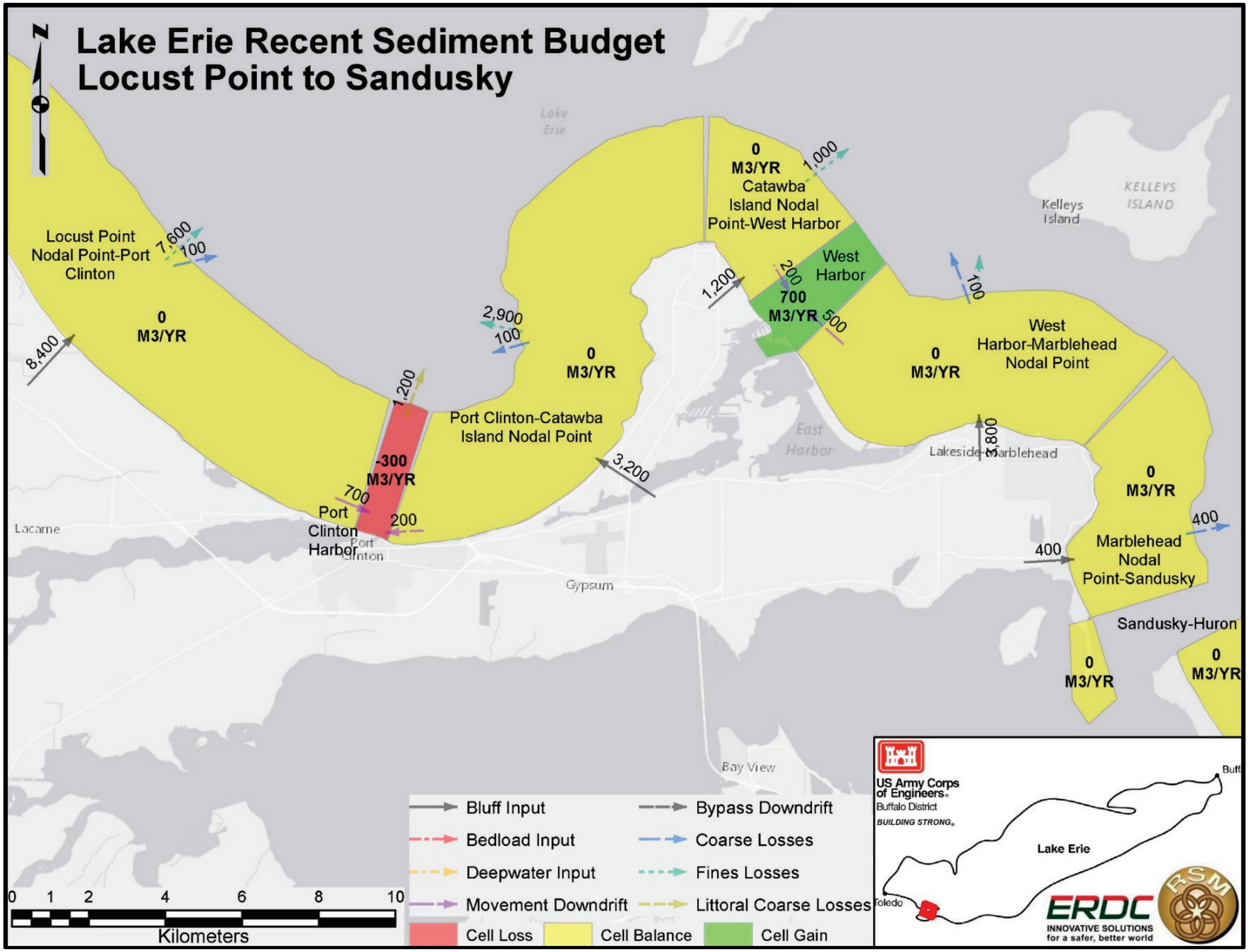


Figure B-8. Locust Point to Sandusky Future sediment budget.

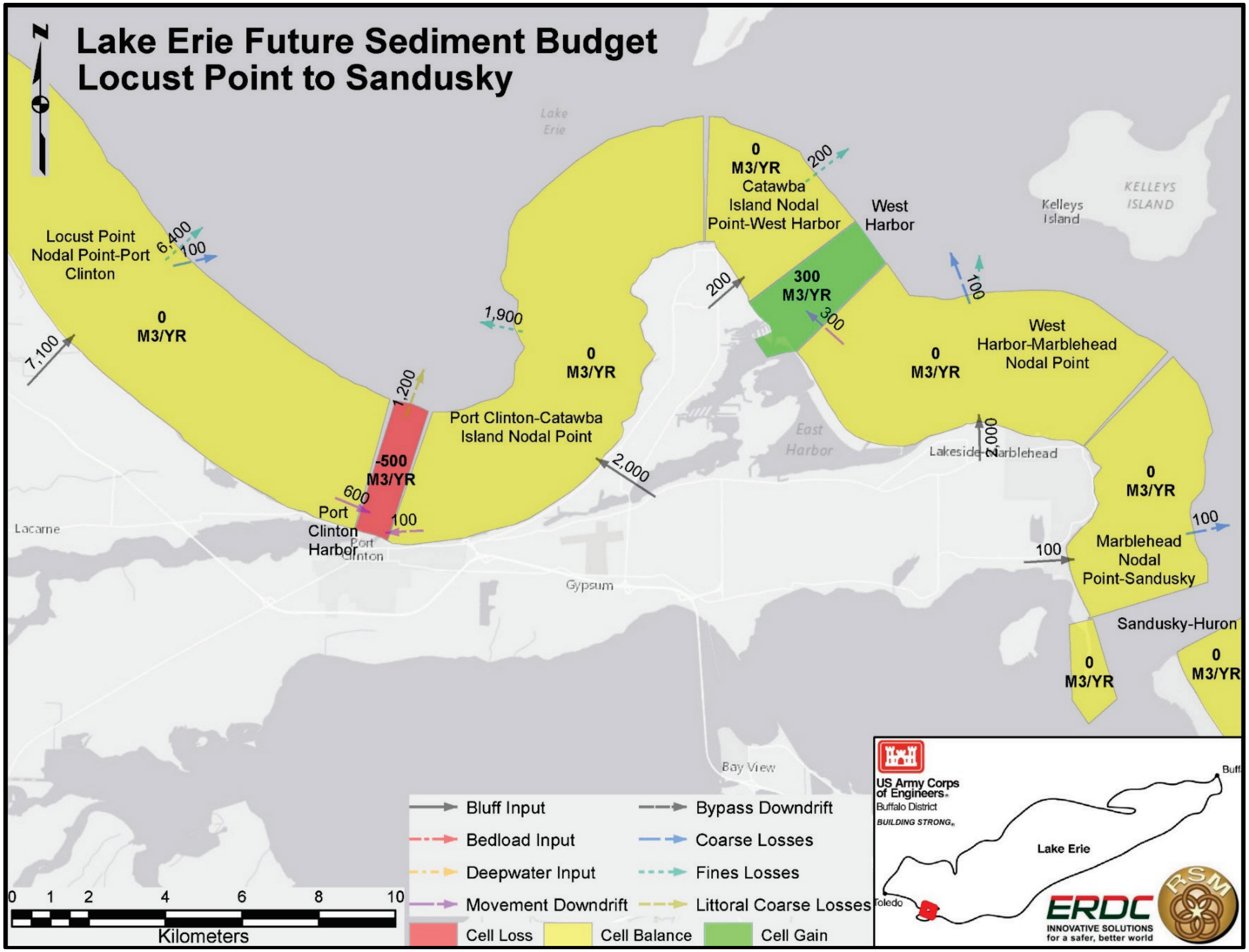


Figure B-9. Sandusky to Beaver Park Marina Pre-Armoring sediment budget.

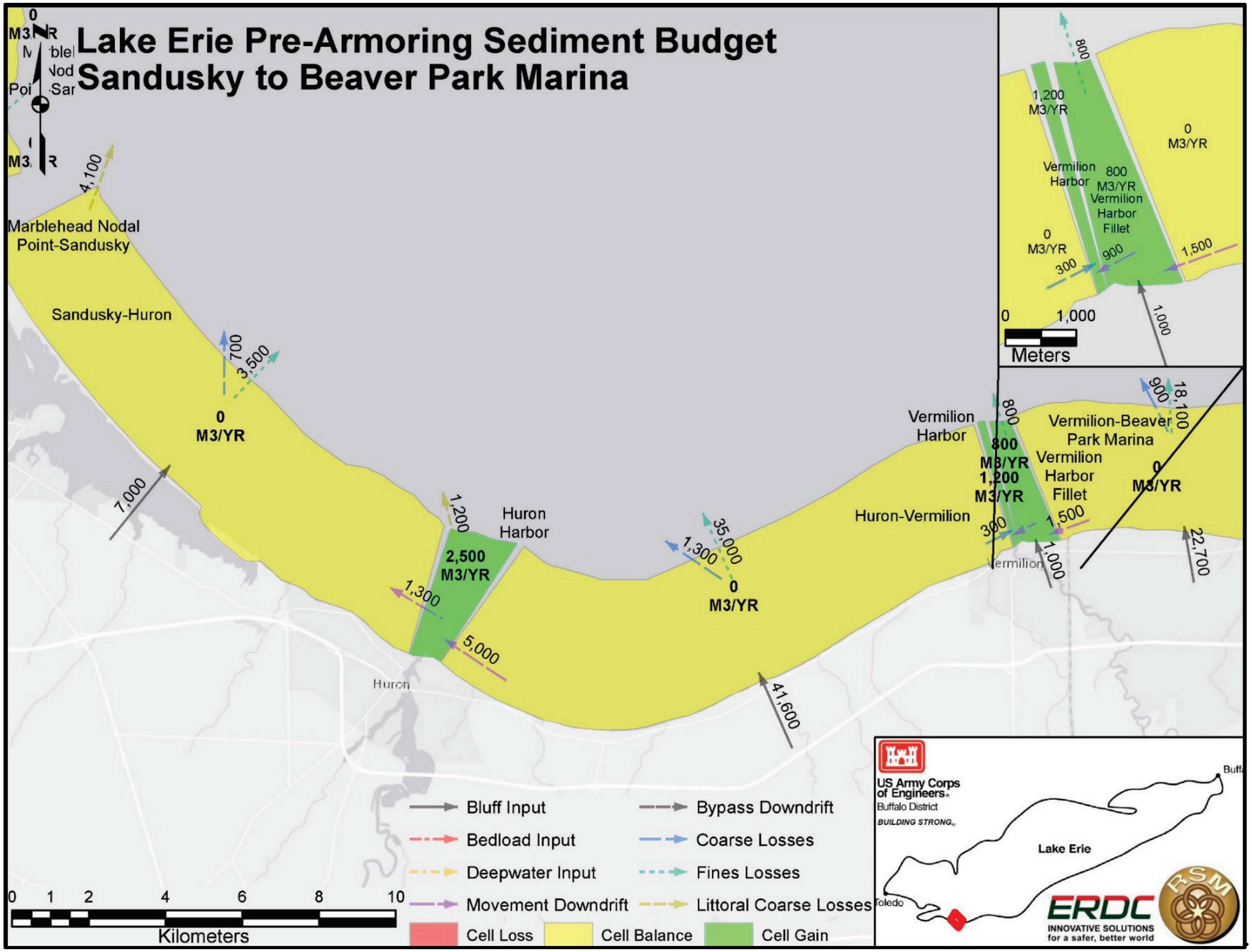


Figure B-10. Sandusky to Beaver Park Marina Mid-Century sediment budget.

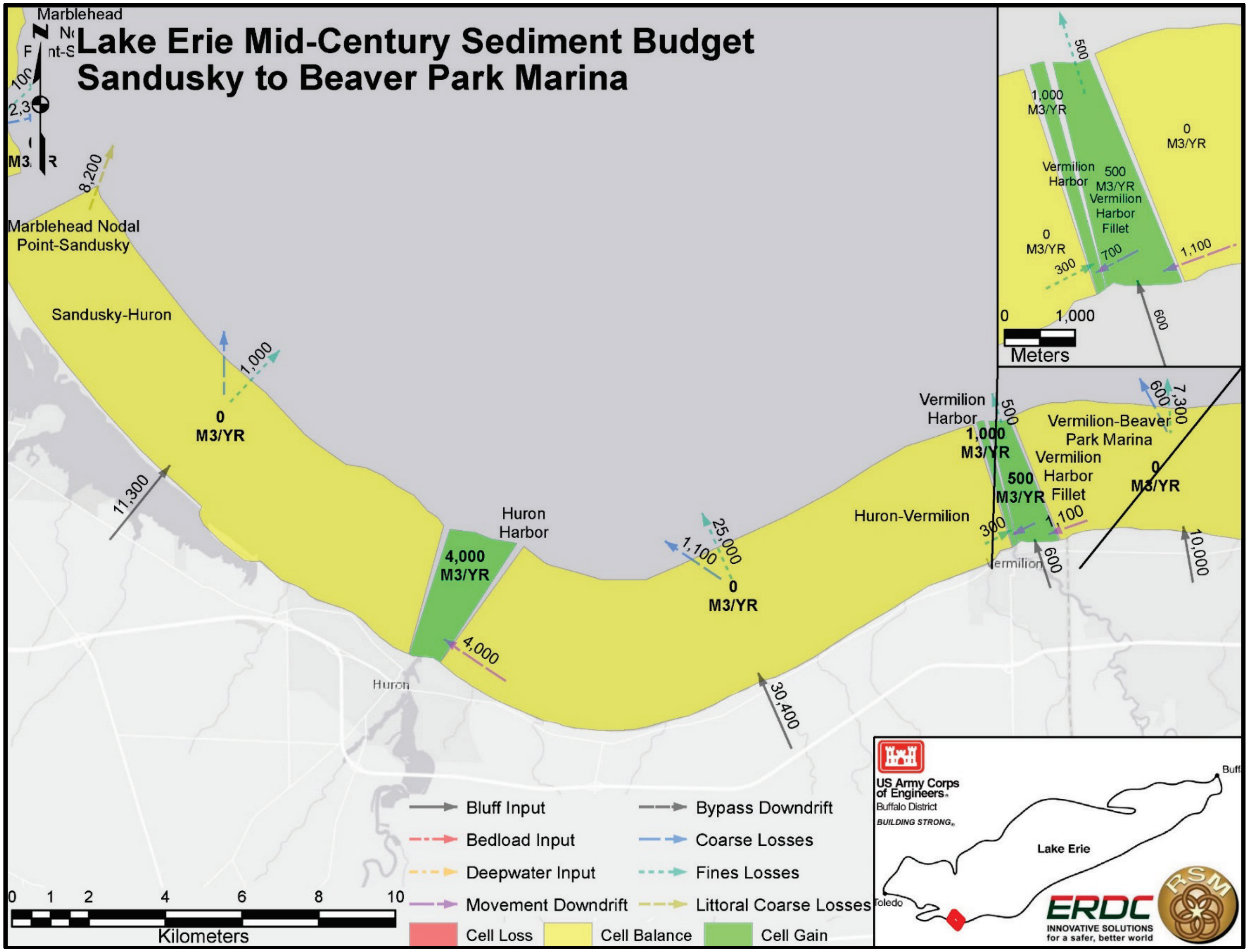


Figure B-11. Sandusky to Beaver Park Marina Recent sediment budget.

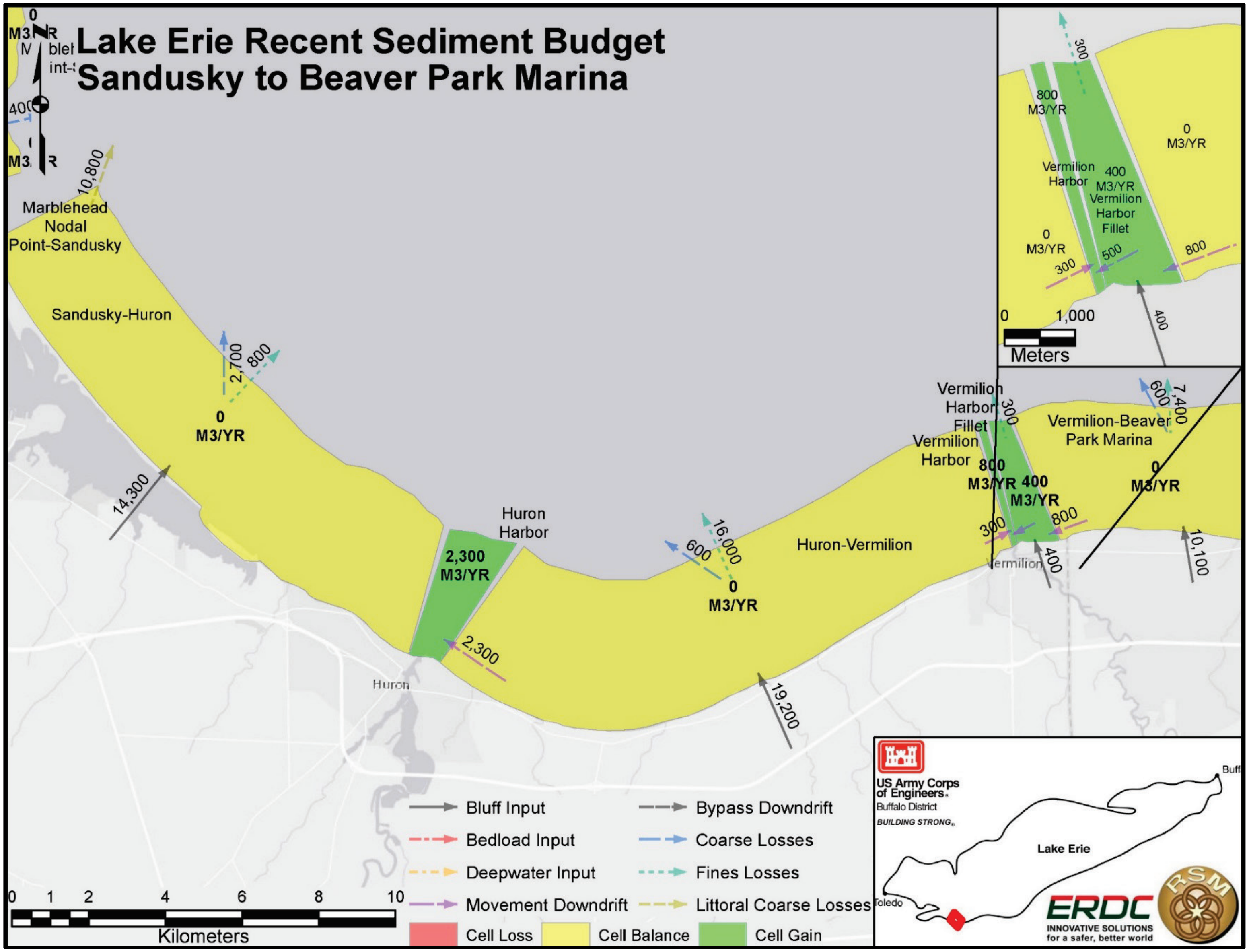


Figure B-12. Sandusky to Beaver Park Marina Future sediment budget.

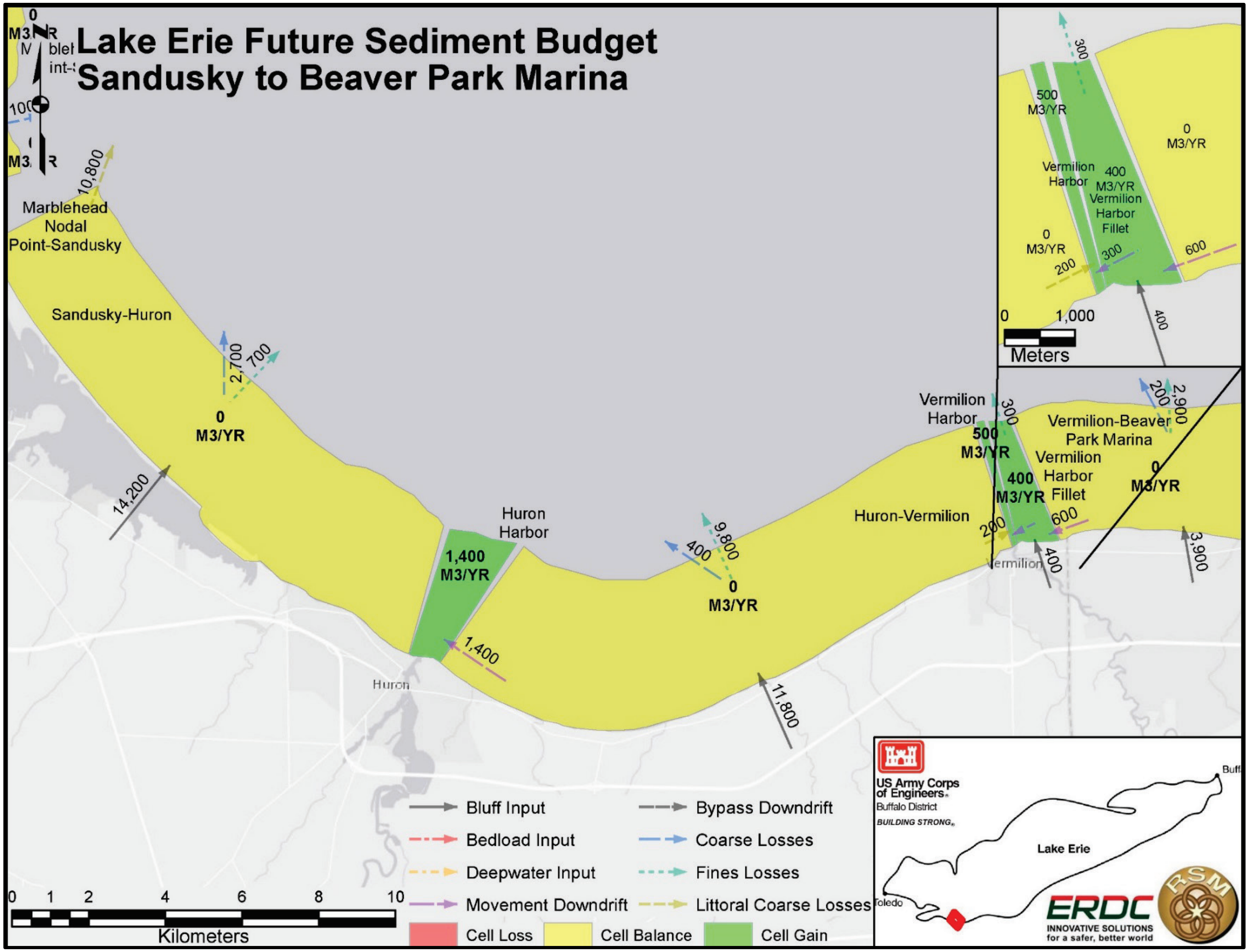


Figure B-13. Beaver Park Marina to Avon Lake Nodal Point Pre-Armoring sediment budget.

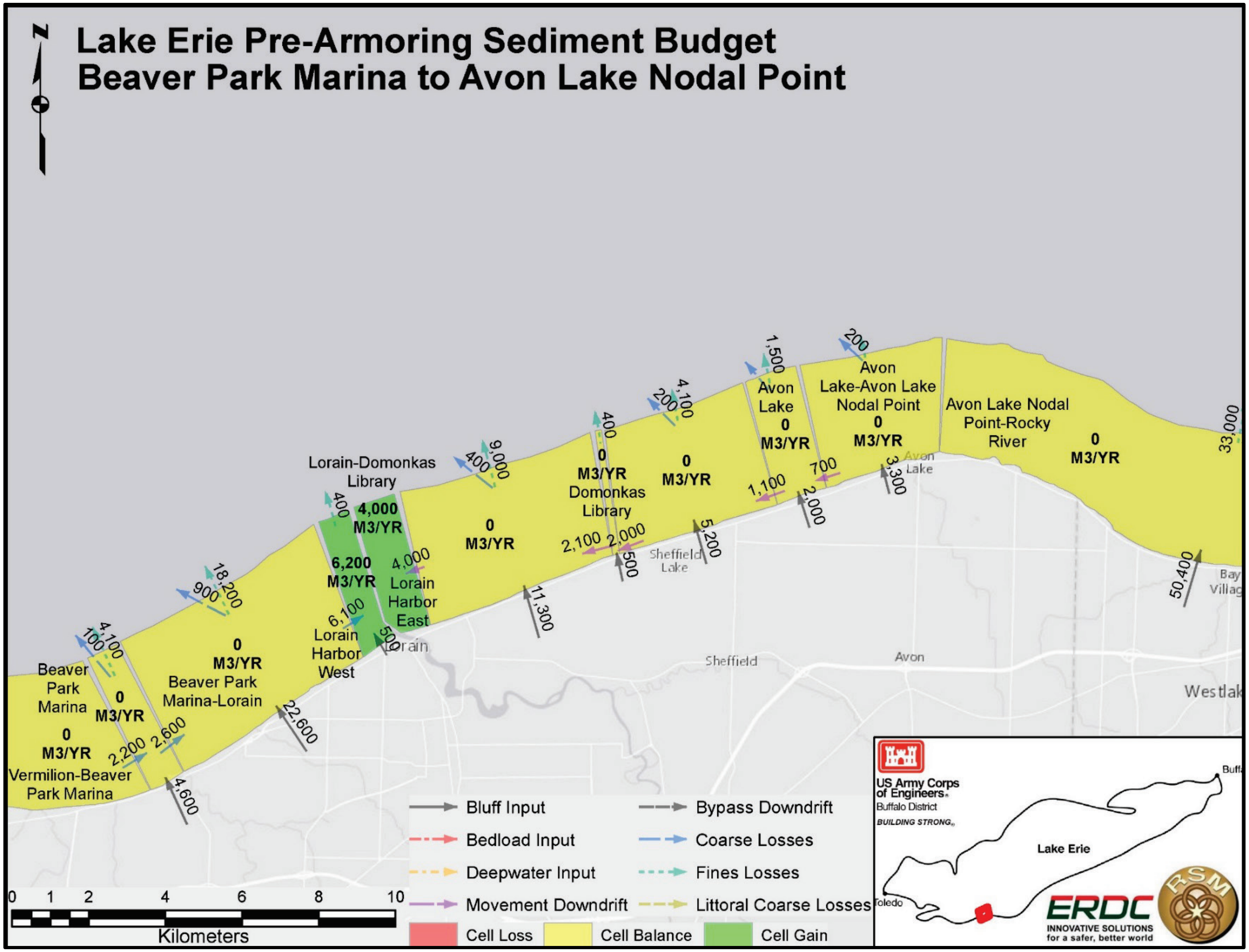


Figure B-14. Beaver Park Marina to Avon Lake Nodal Point Mid-Century sediment budget.

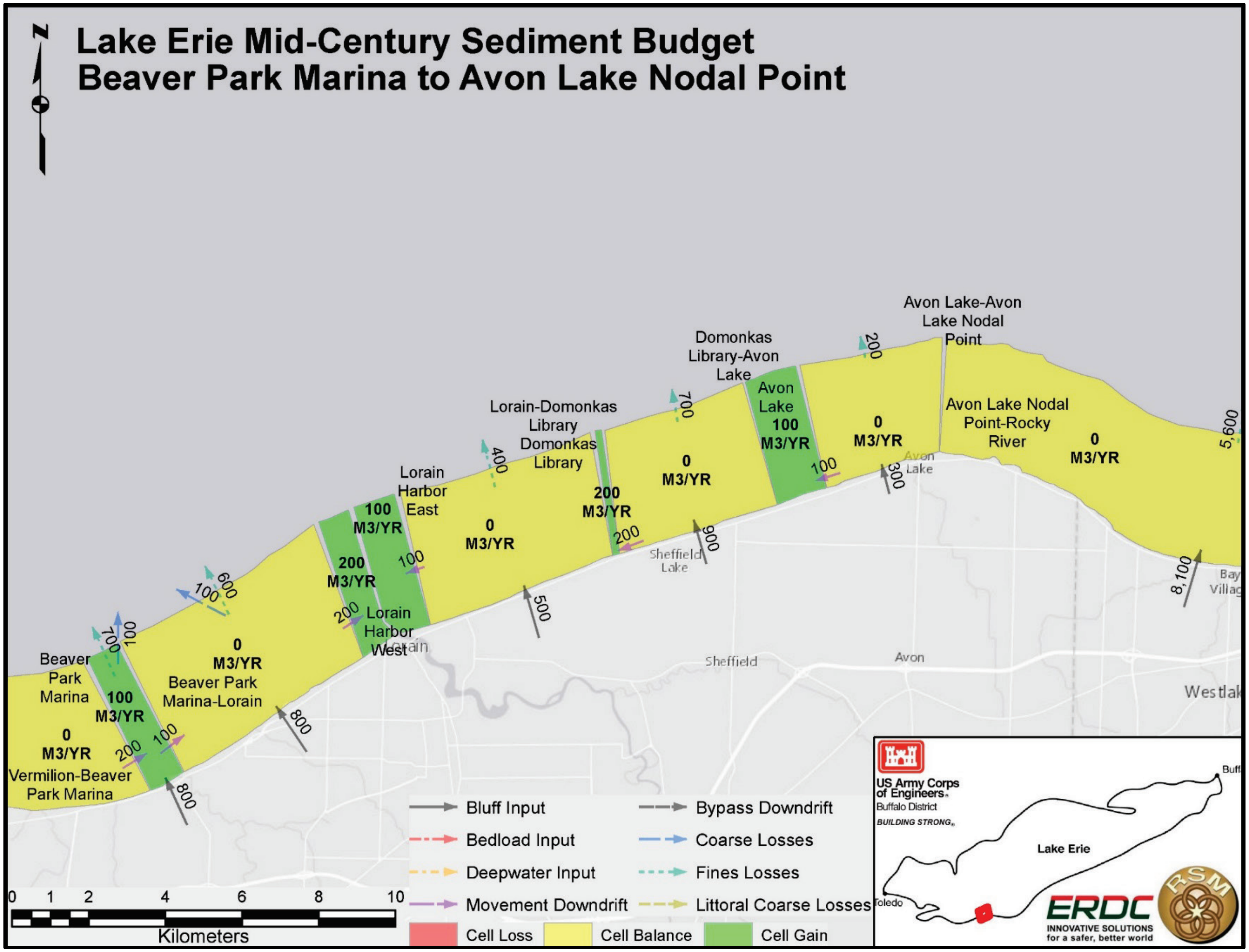


Figure B-15. Beaver Park Marina to Avon Lake Nodal Point Recent sediment budget.

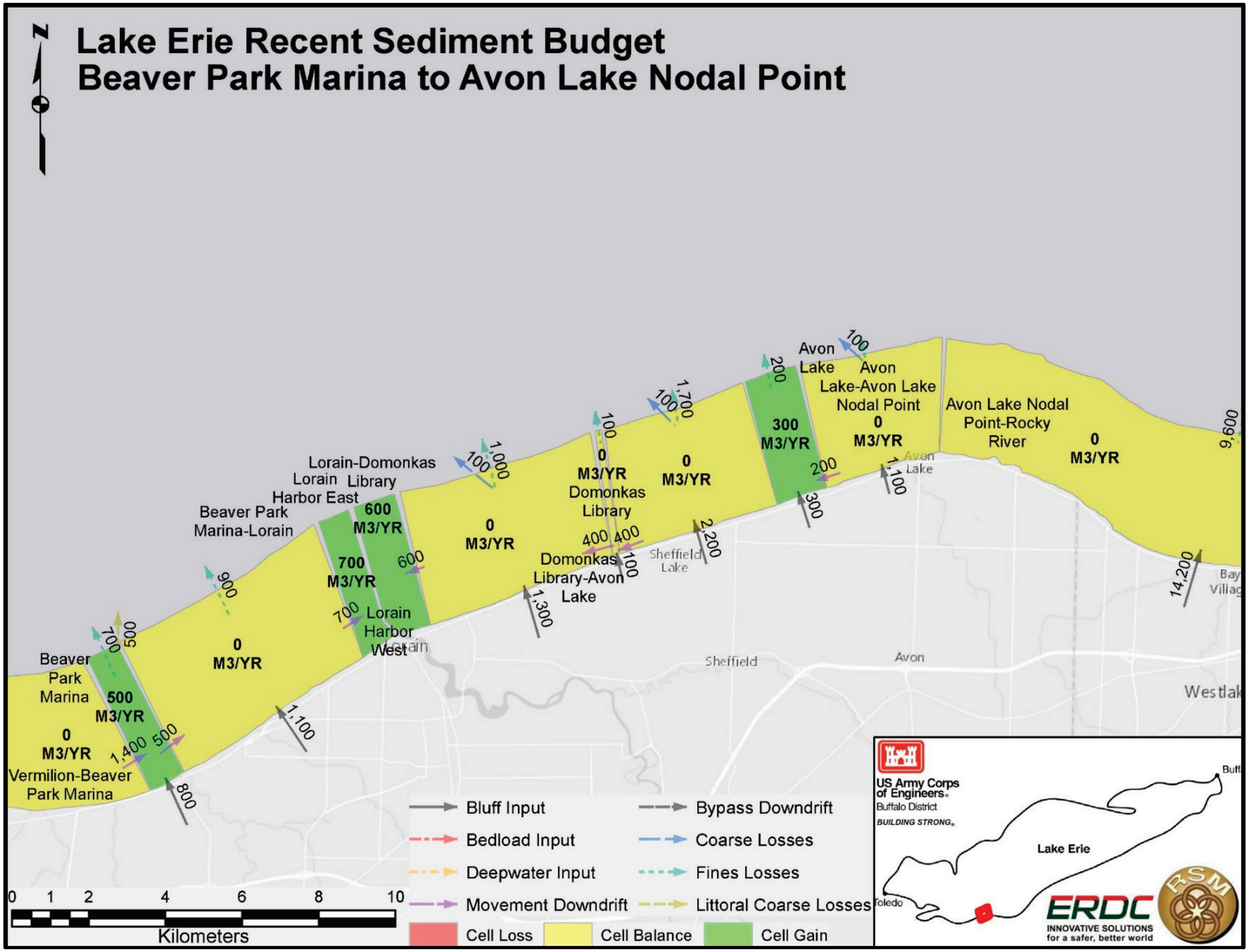


Figure B-16. Beaver Park Marina to Avon Lake Nodal Point Future sediment budget.

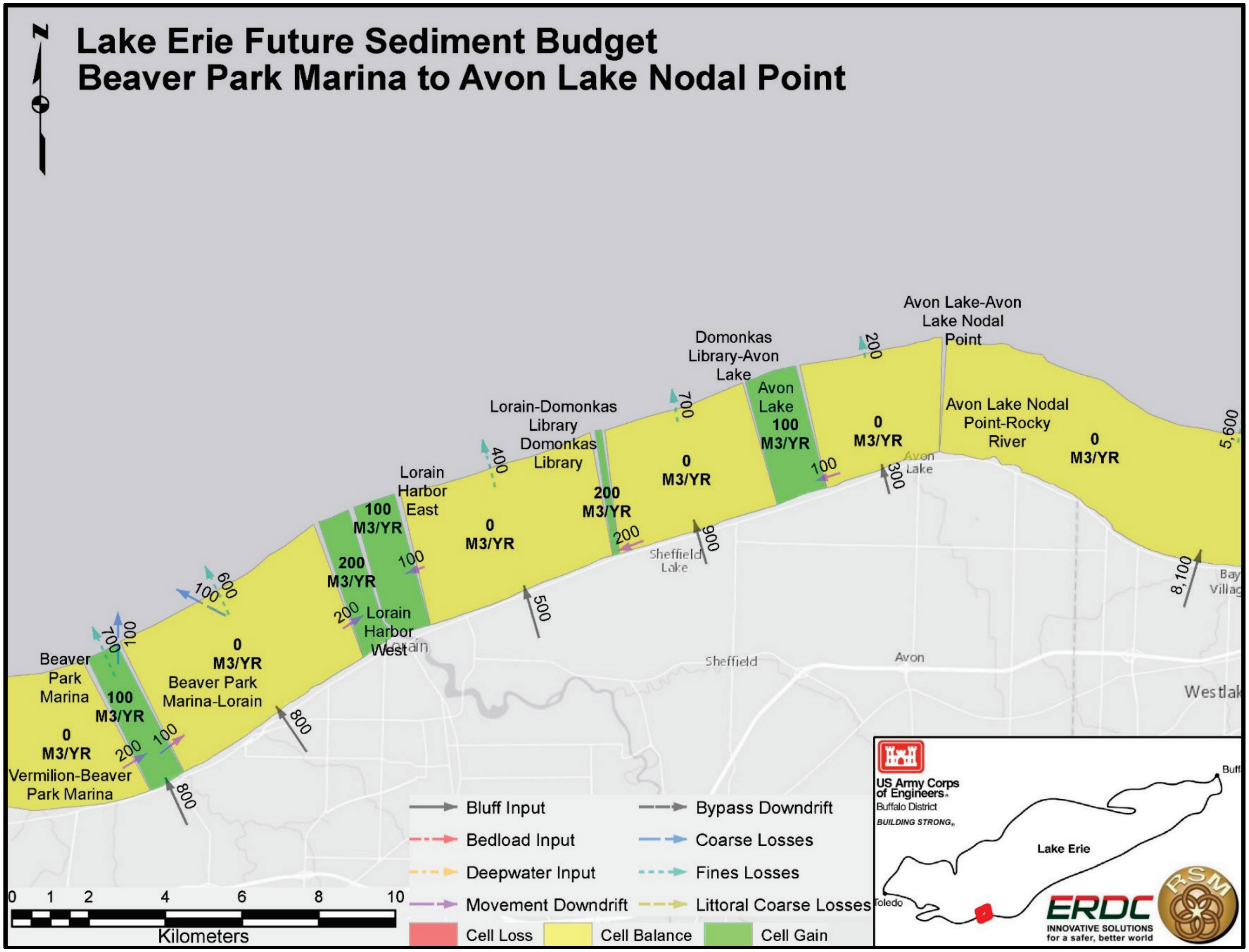


Figure B-17. Avon Lake Nodal Point to Cleveland Pre-Armoring sediment budget.

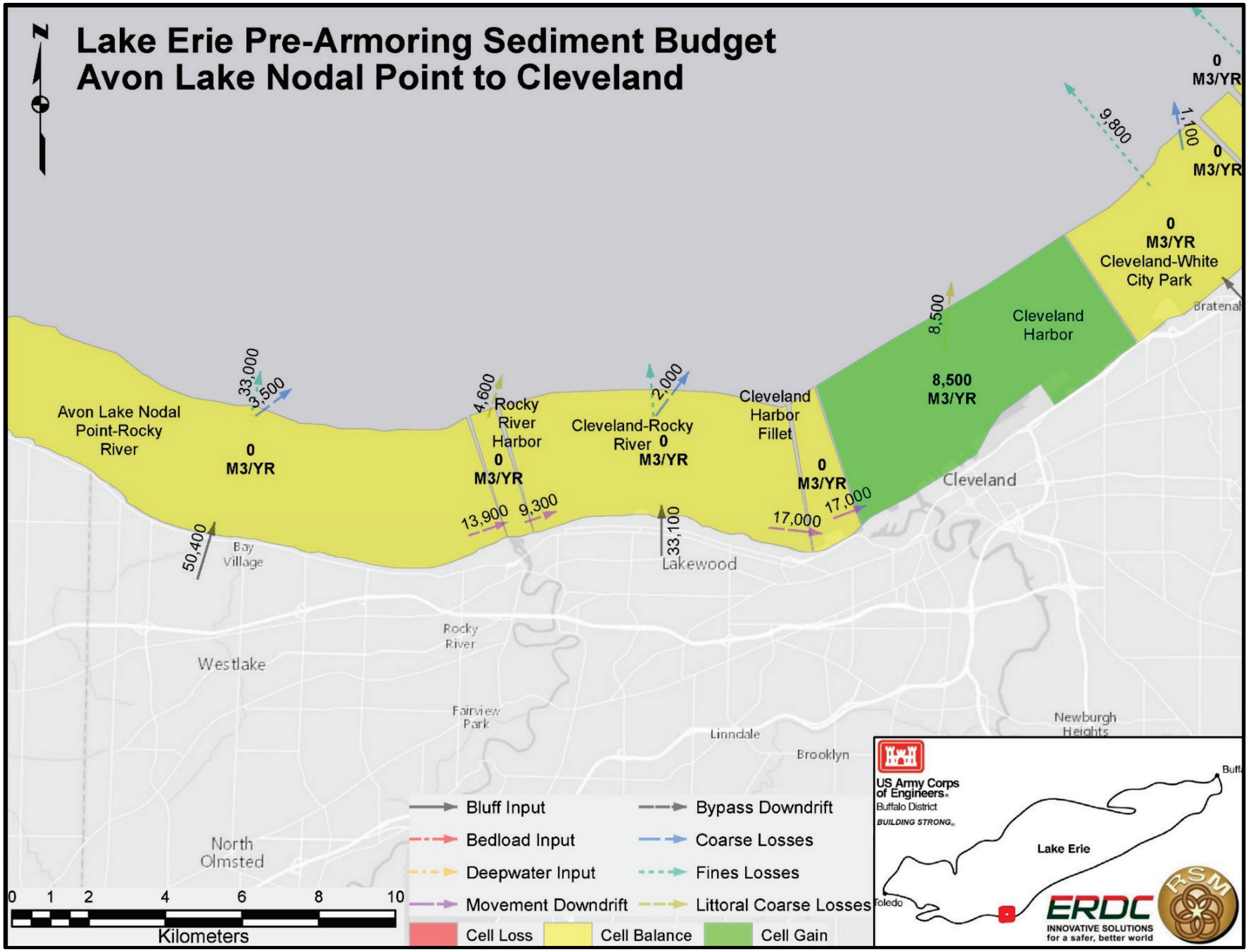


Figure B-18. Avon Lake Nodal Point to Cleveland Mid-Century sediment budget

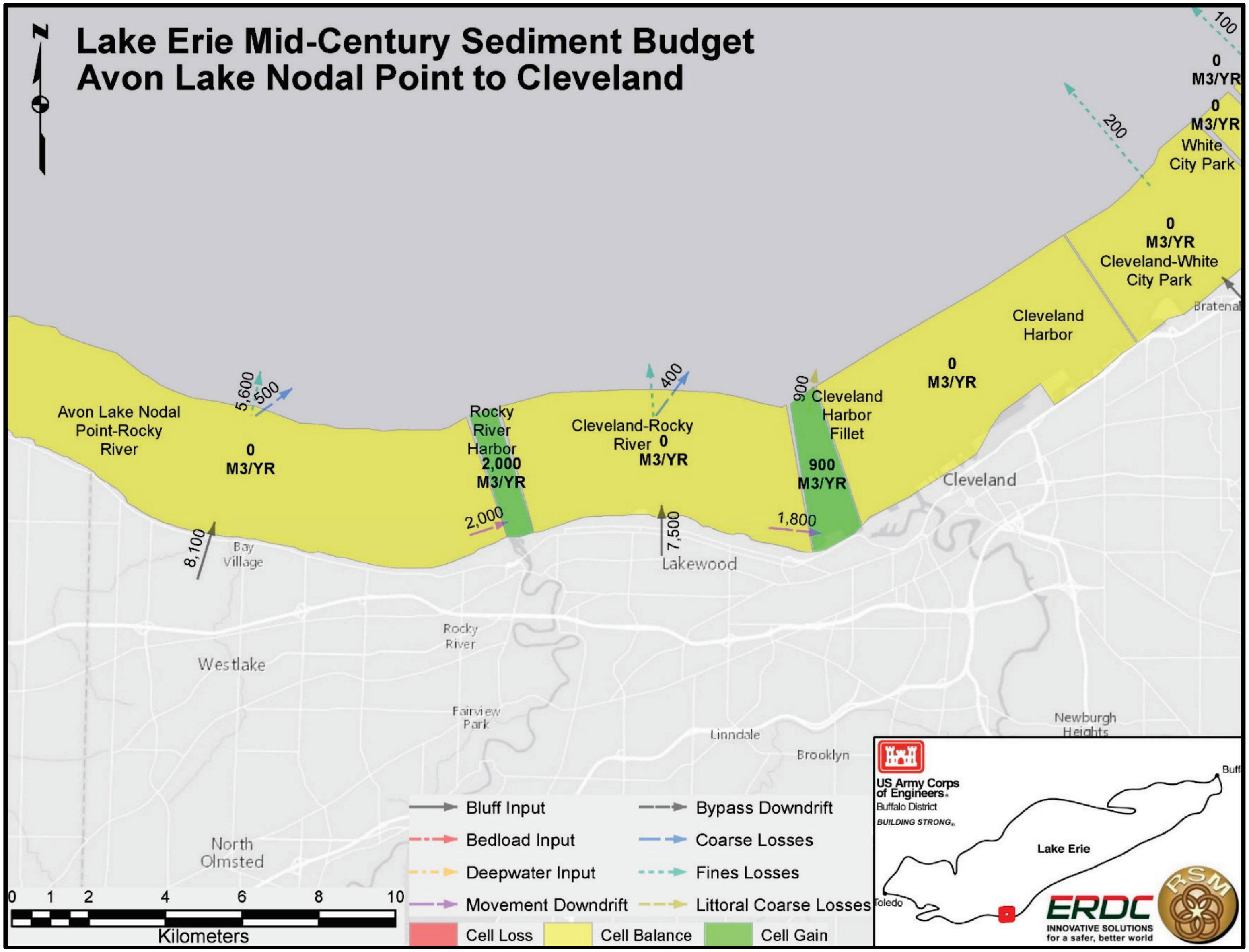


Figure B-19. Avon Lake Nodal Point to Cleveland Recent sediment budget.

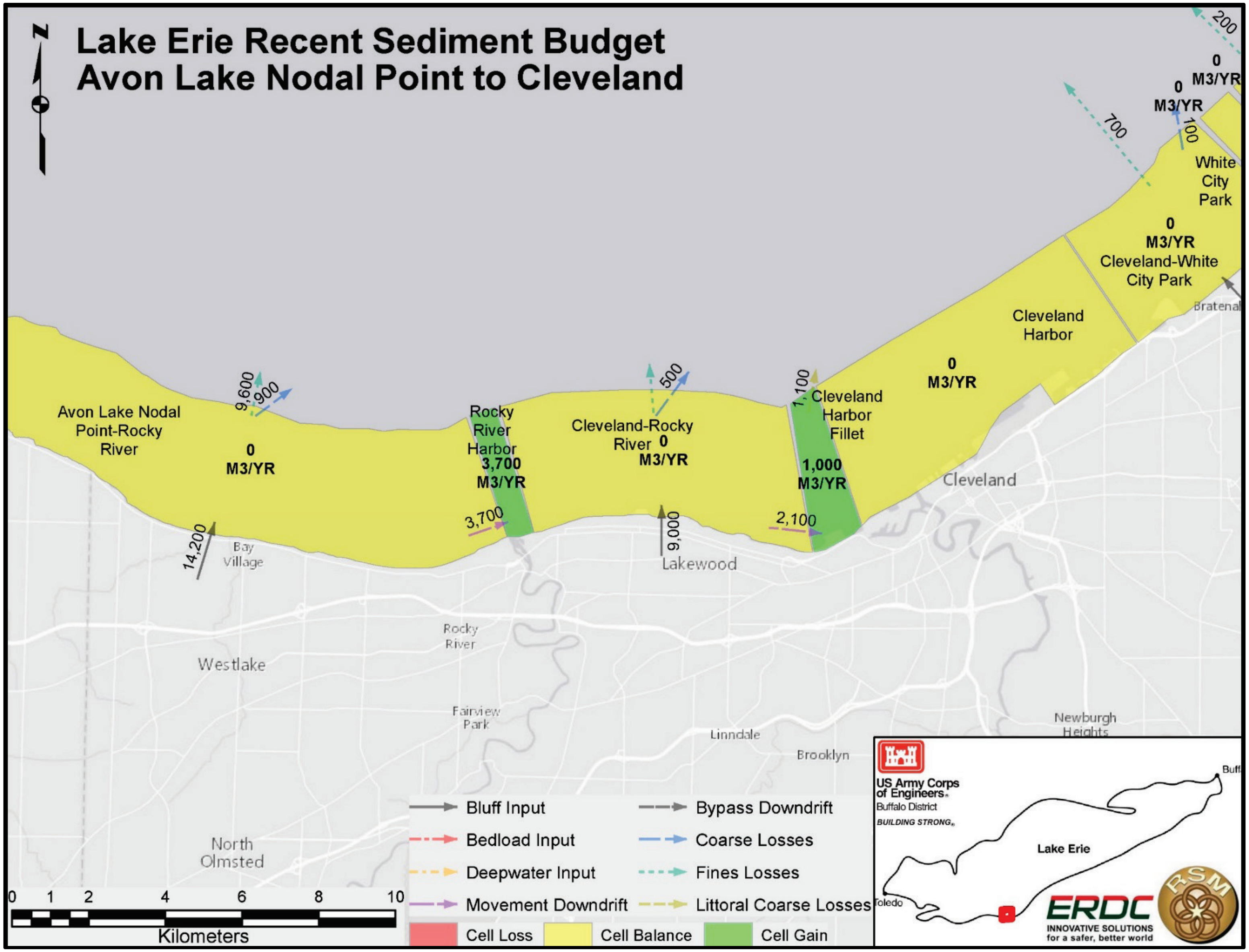


Figure B-20. Avon Lake Nodal Point to Cleveland Future sediment budget.

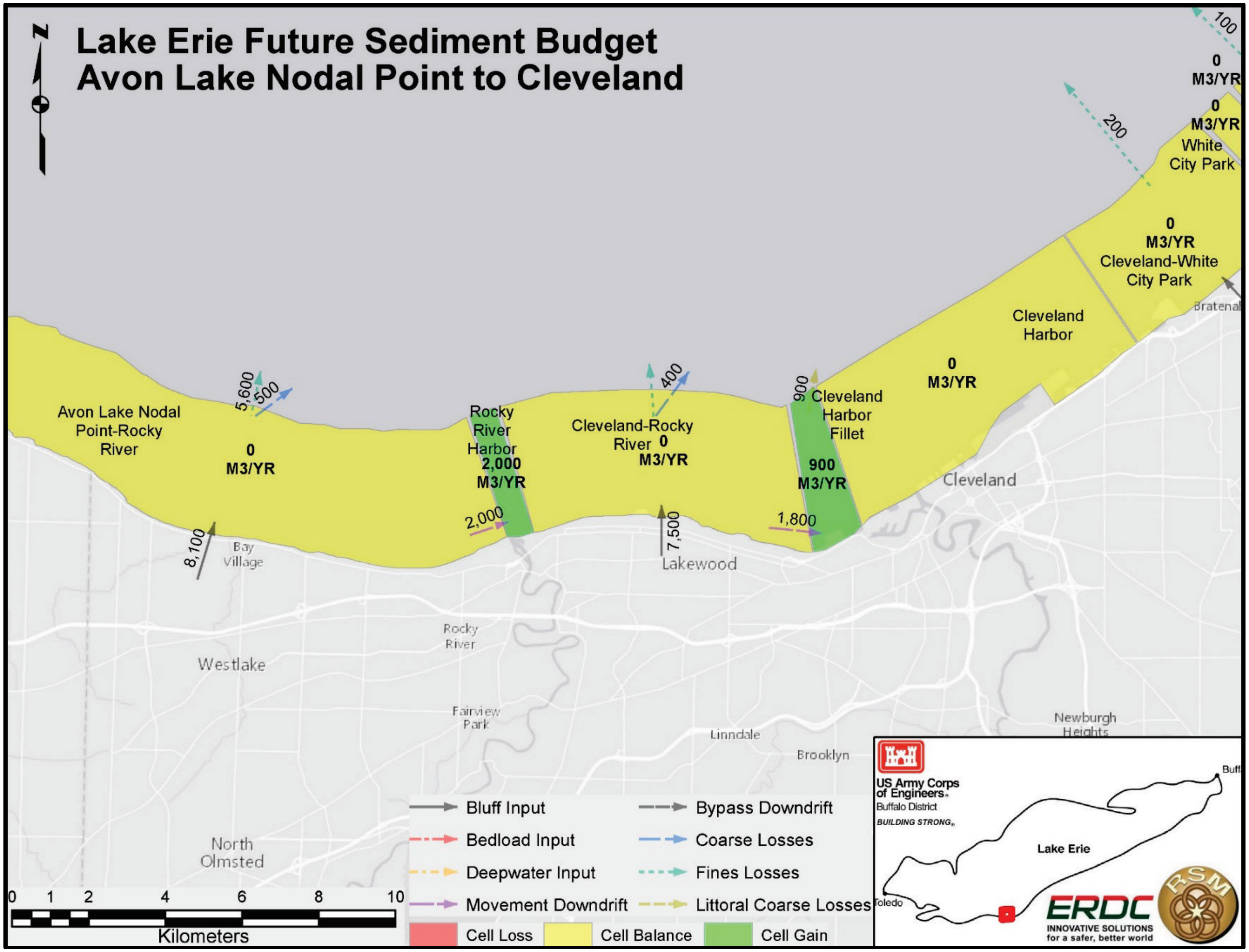


Figure B-21. Cleveland to Eastlake Pre-Armoring sediment budget.

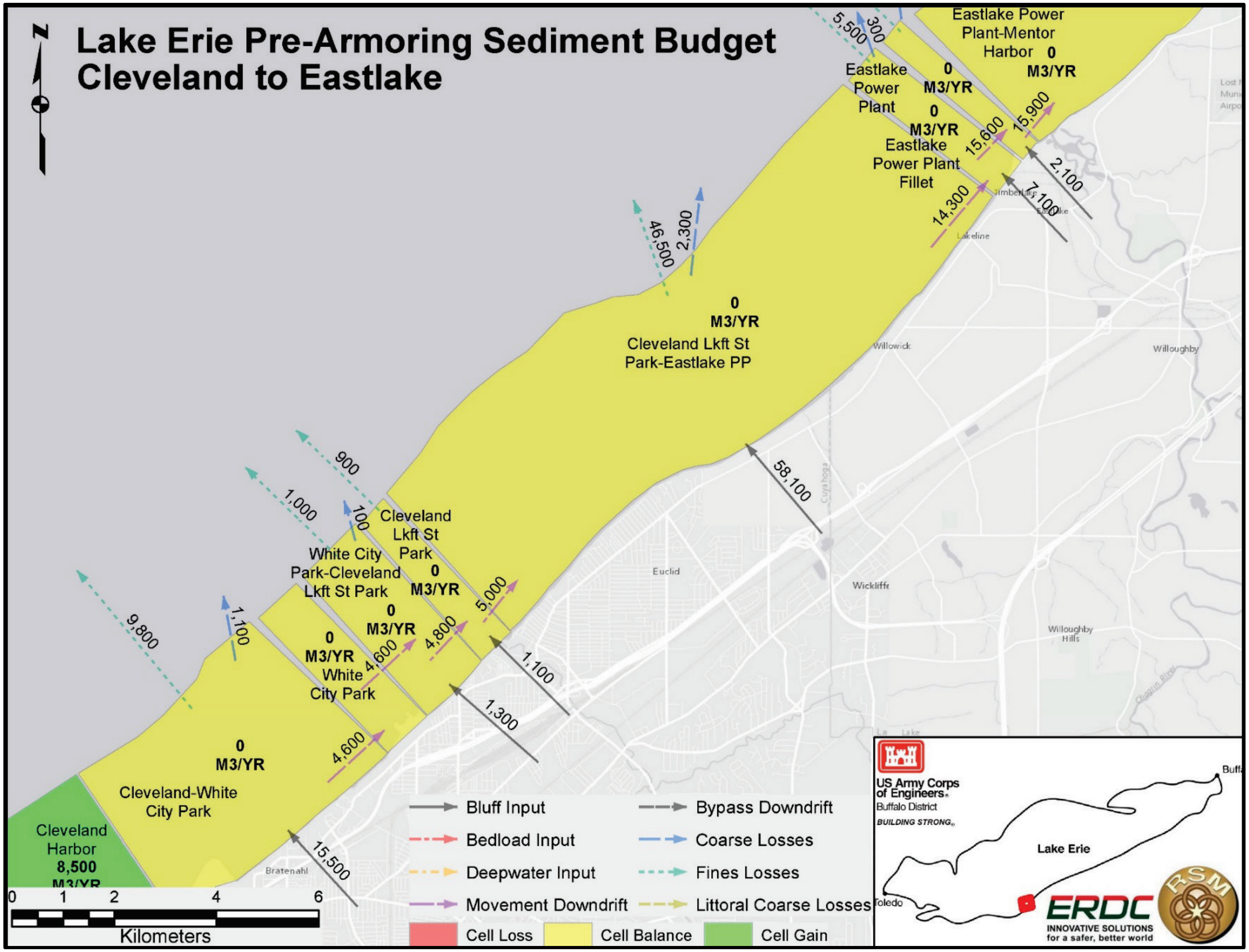


Figure B-22. Cleveland to Eastlake Mid-Century sediment budget.

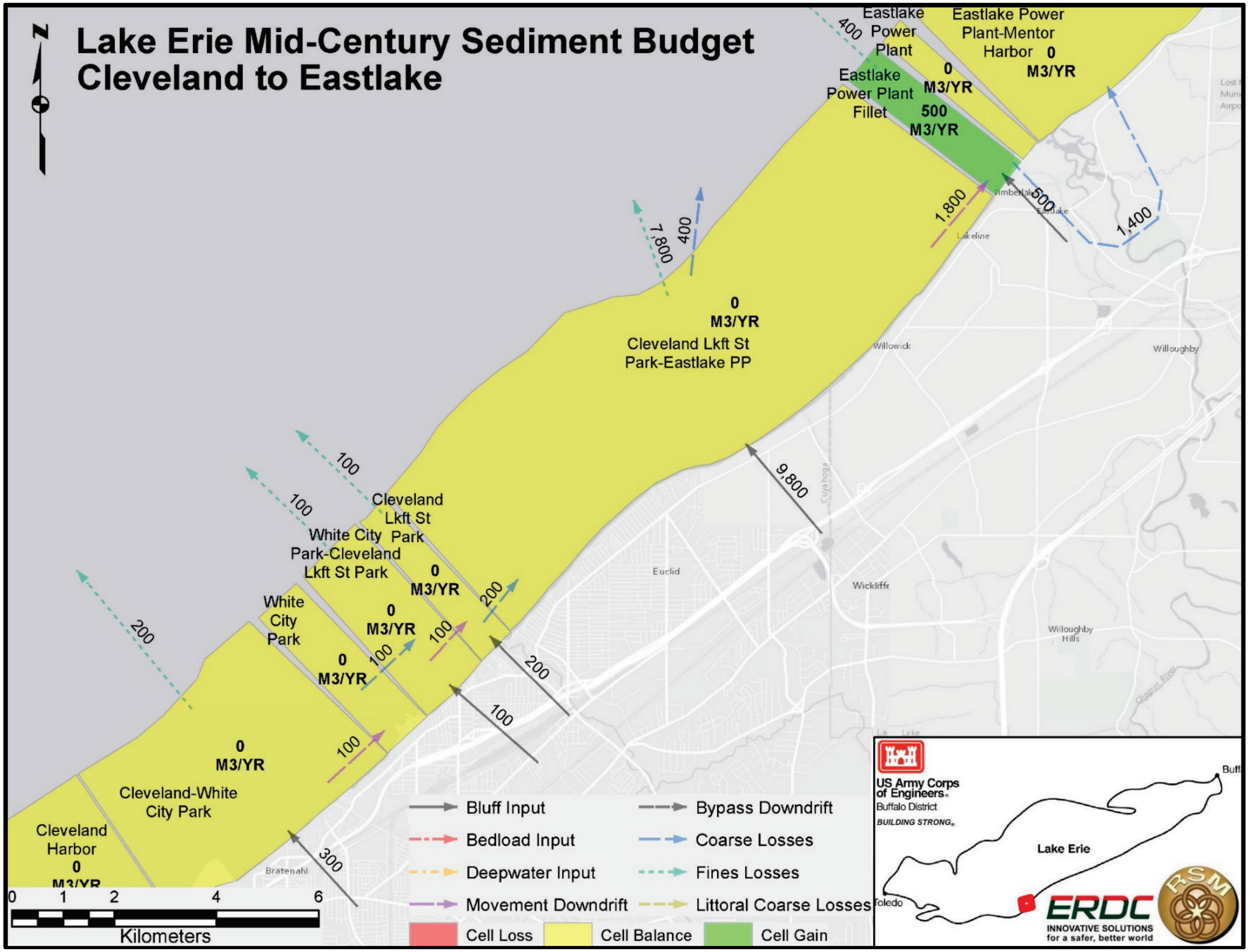


Figure B-23. Cleveland to Eastlake Recent sediment budget.

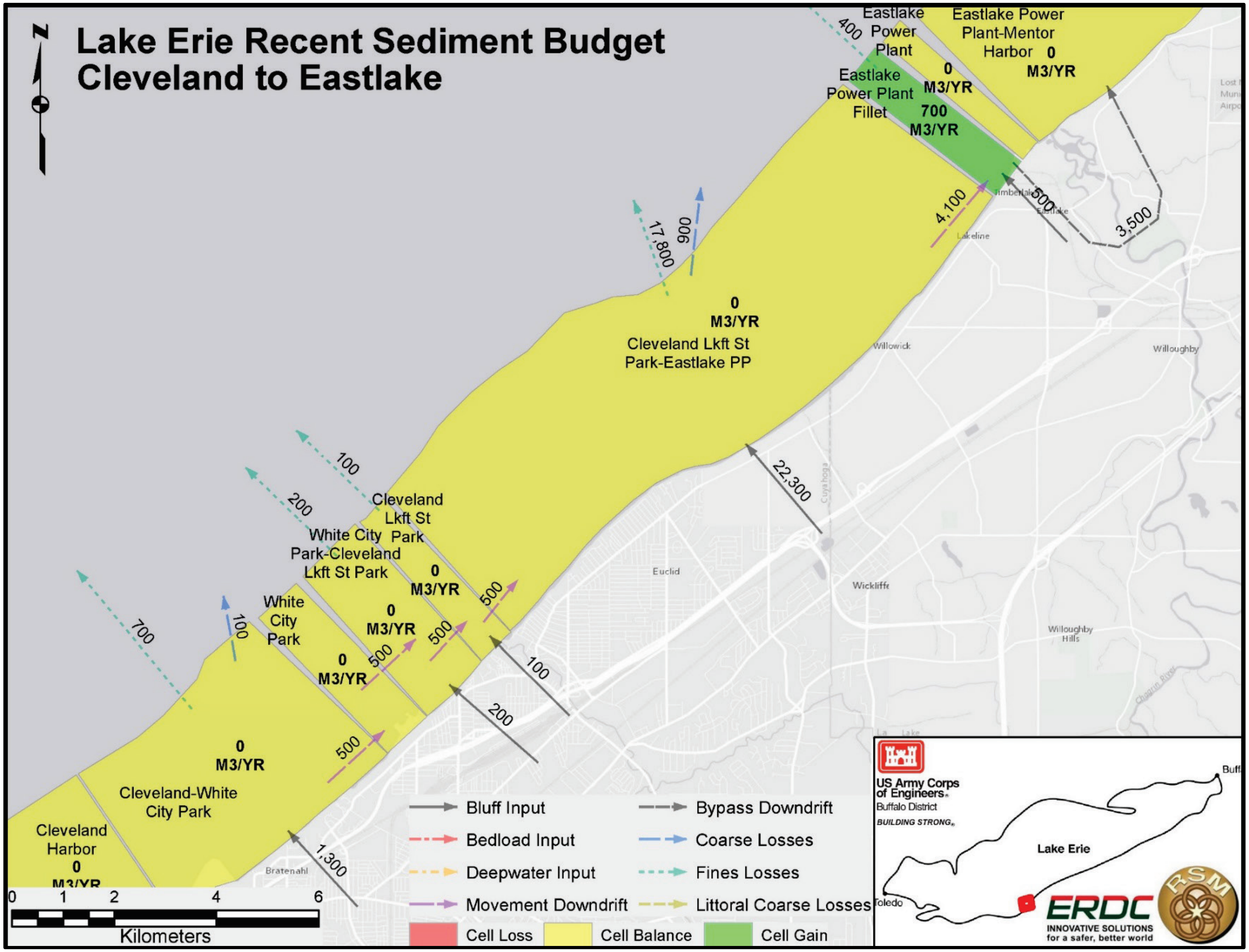


Figure B-24. Cleveland to Eastlake Future sediment budget.

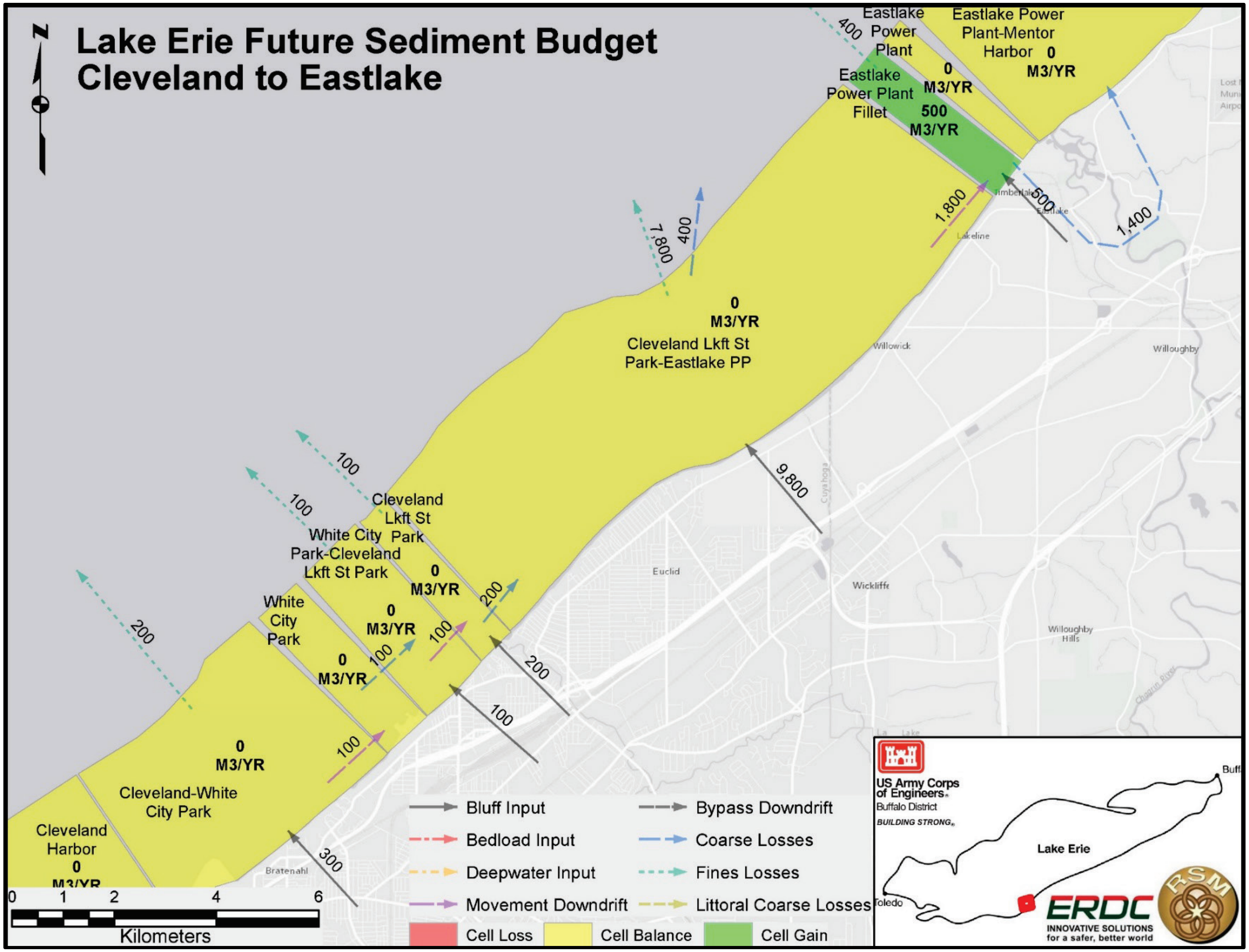


Figure B-25. Eastlake to Fairport Pre-Armoring sediment budget.

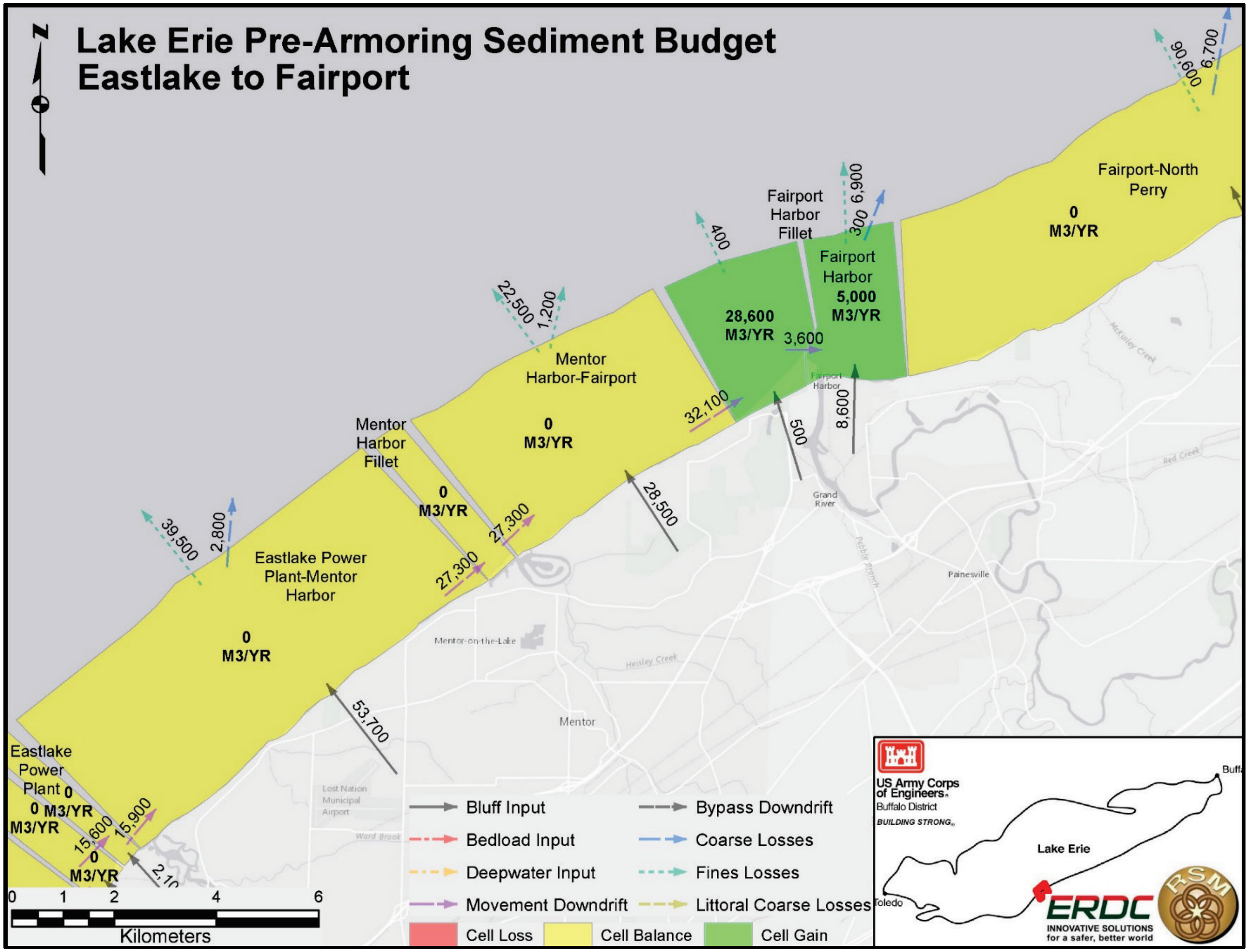


Figure B-26. Eastlake to Fairport Mid-Century sediment budget.

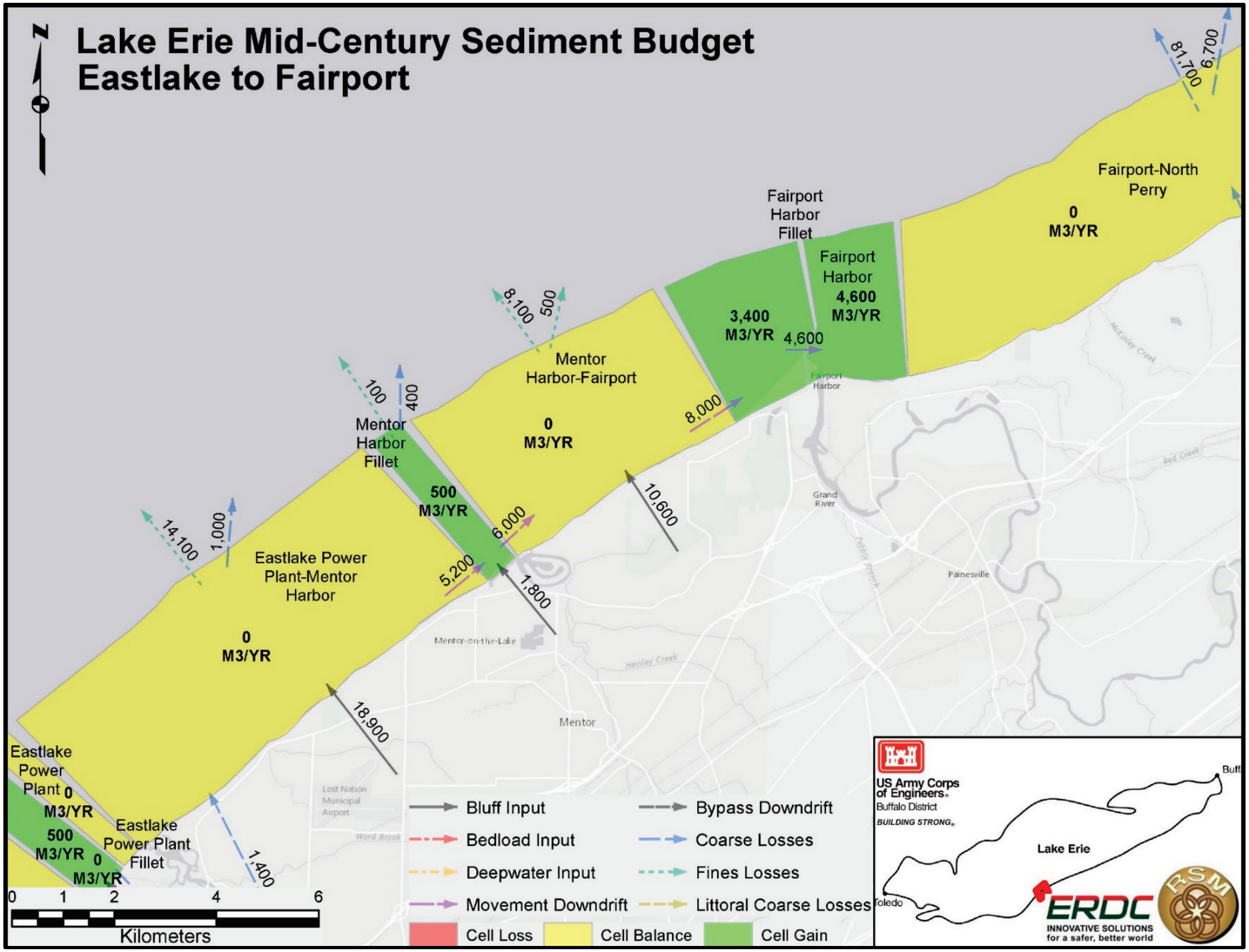


Figure B-27. Eastlake to Fairport Recent sediment budget.

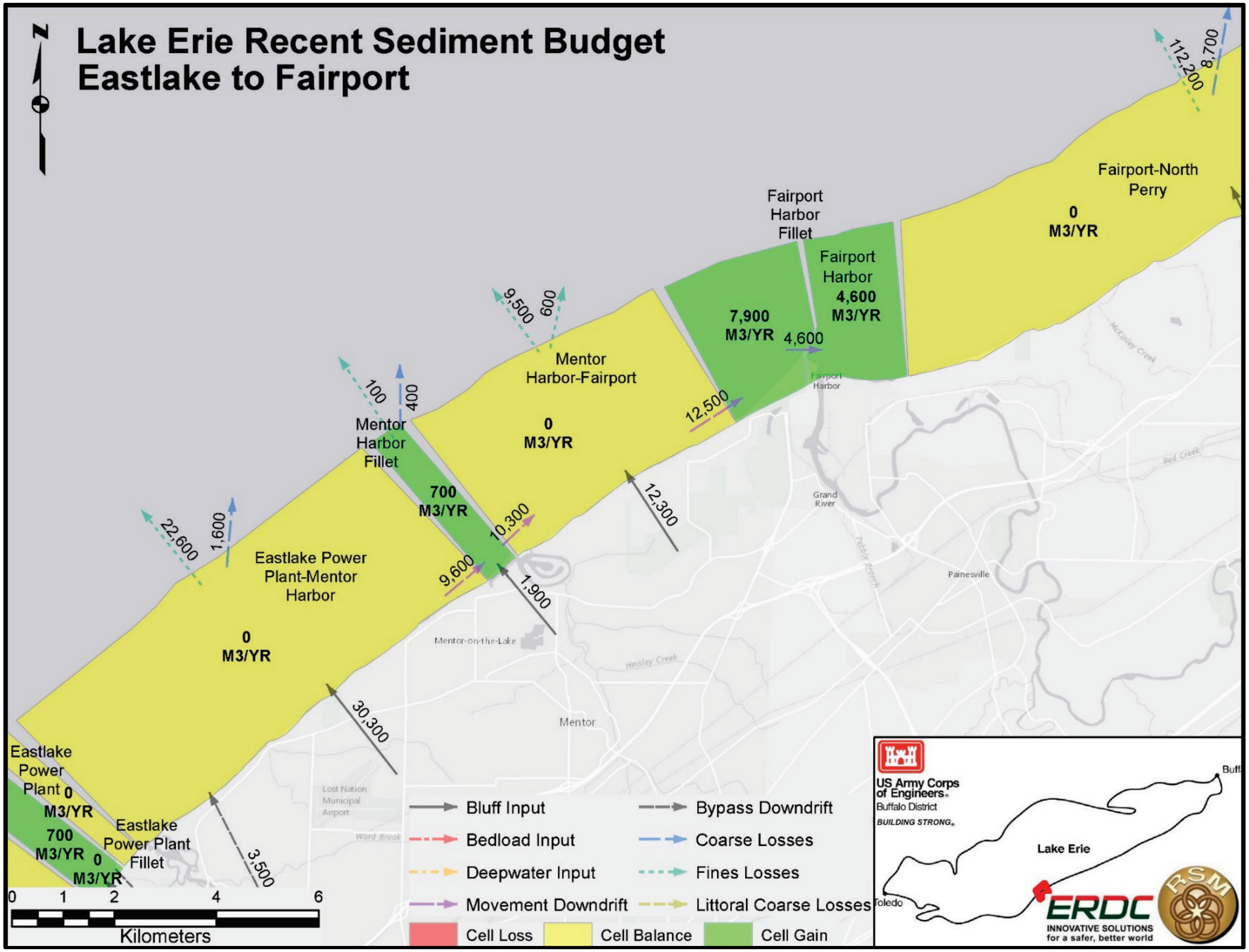


Figure B-28. Eastlake to Fairport Future sediment budget.

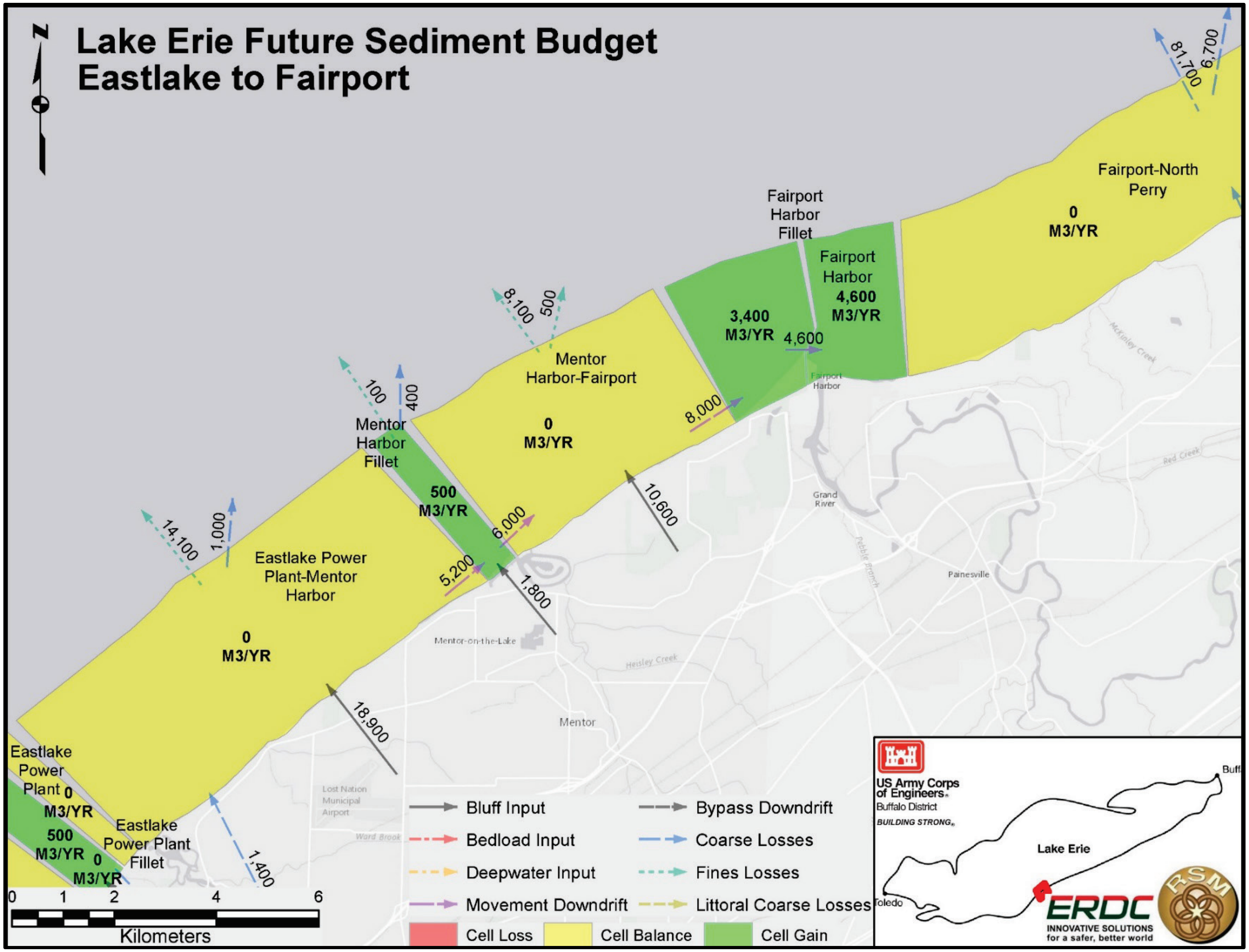


Figure B-29. Fairport to Geneva-on-the-Lake Pre-Armoring sediment budget.

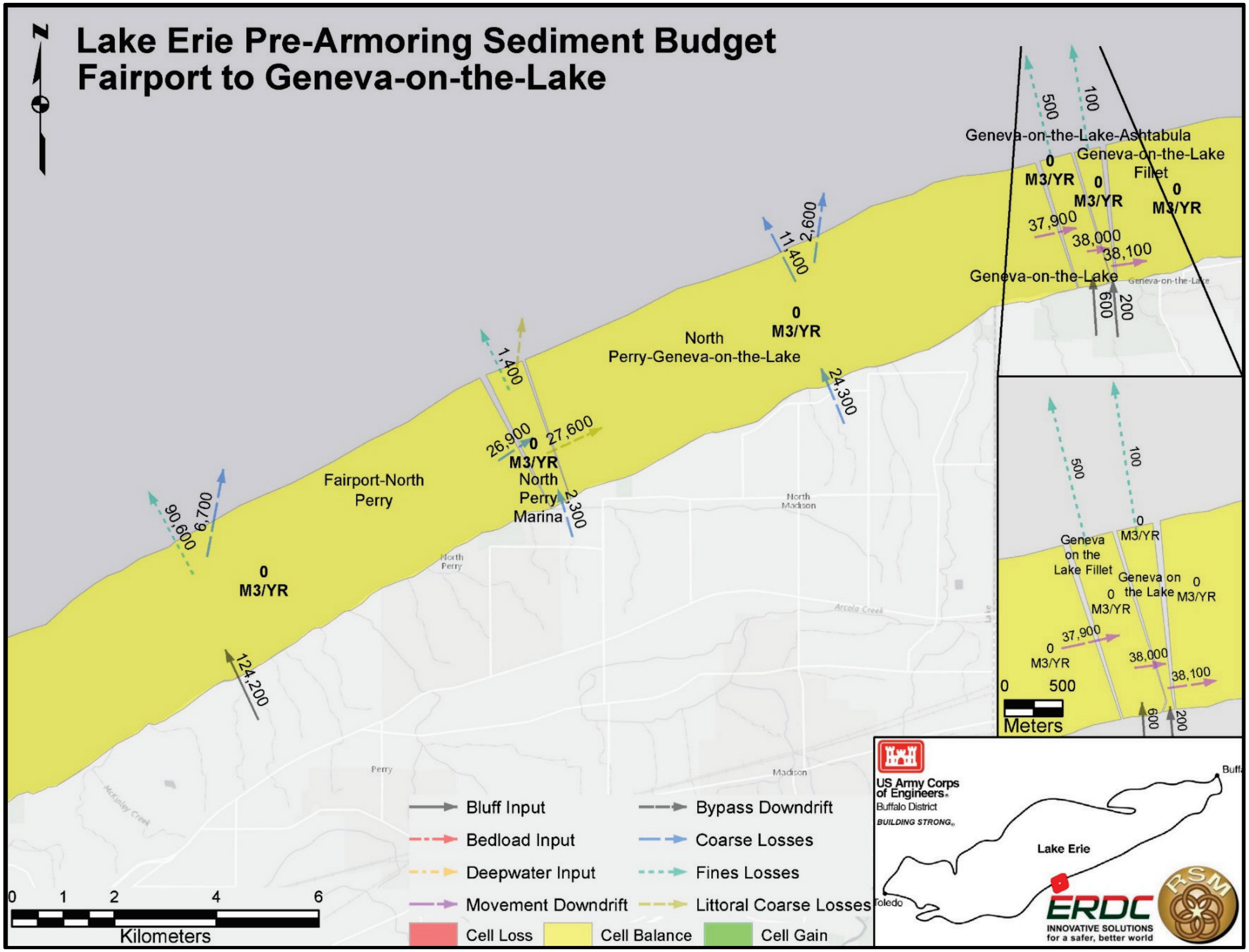


Figure B-30. Fairport to Geneva-on-the-Lake Mid-Century sediment budget.

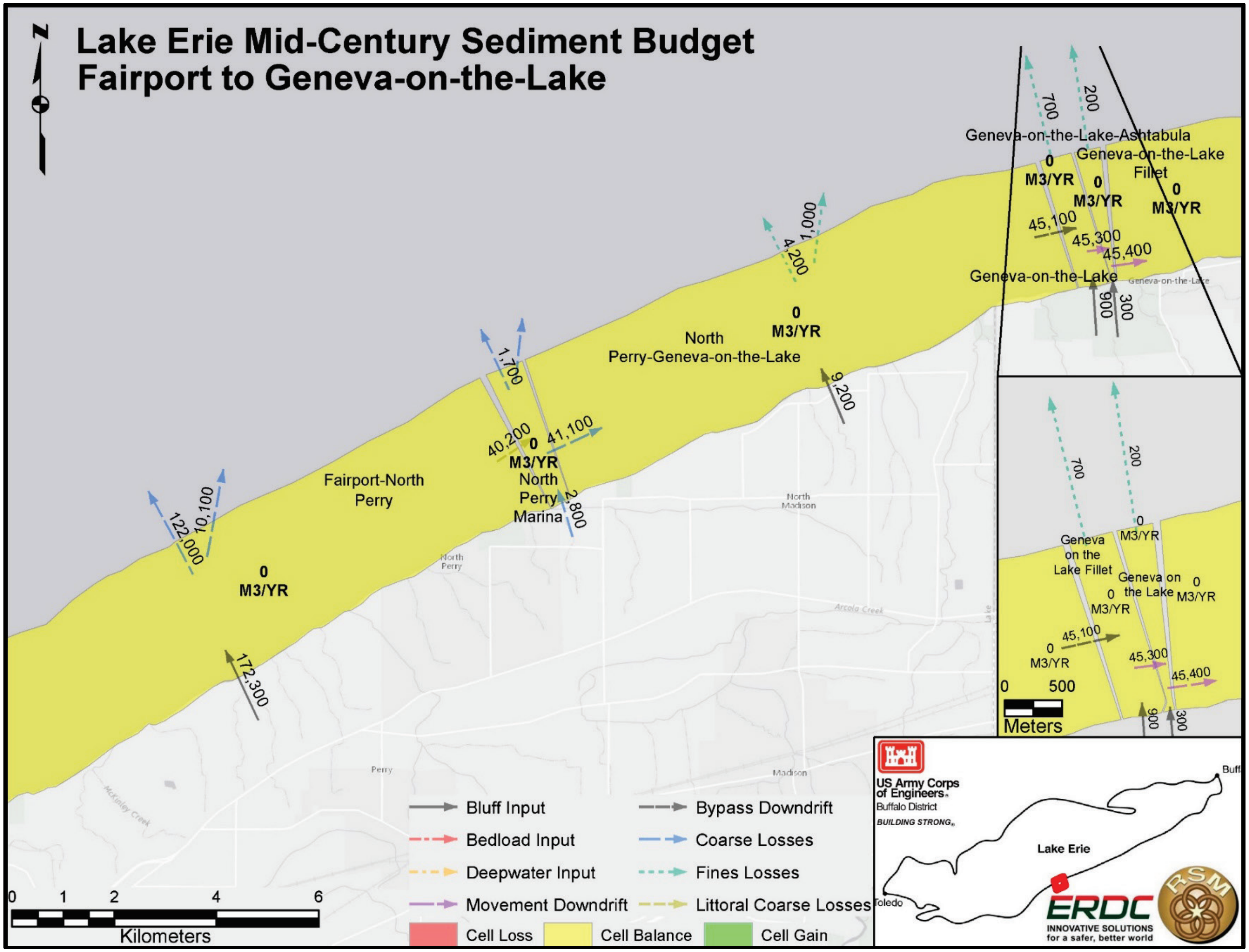


Figure B-31. Fairport to Geneva-on-the-Lake Recent sediment budget.

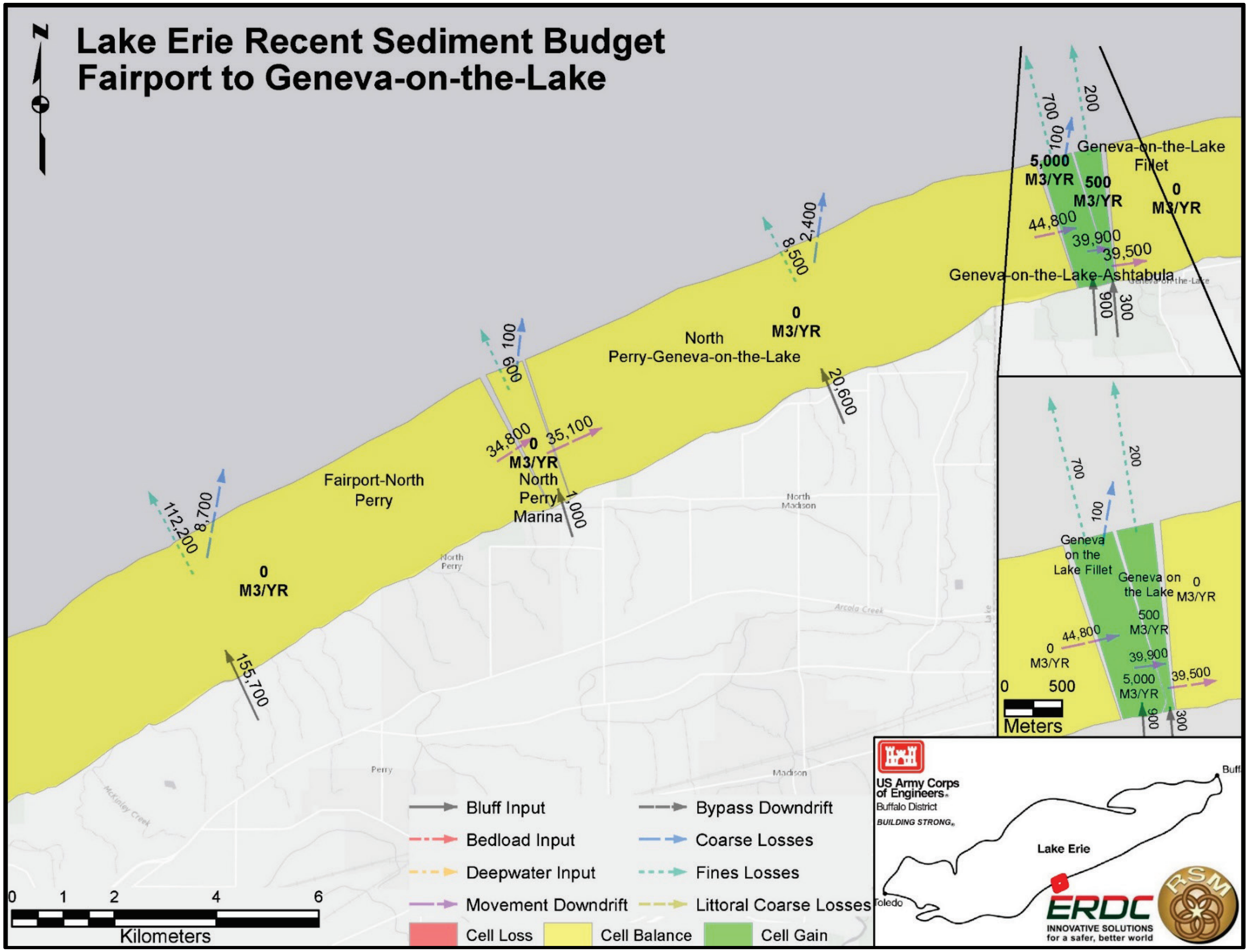


Figure B-32. Fairport to Geneva-on-the-Lake Future sediment budget.

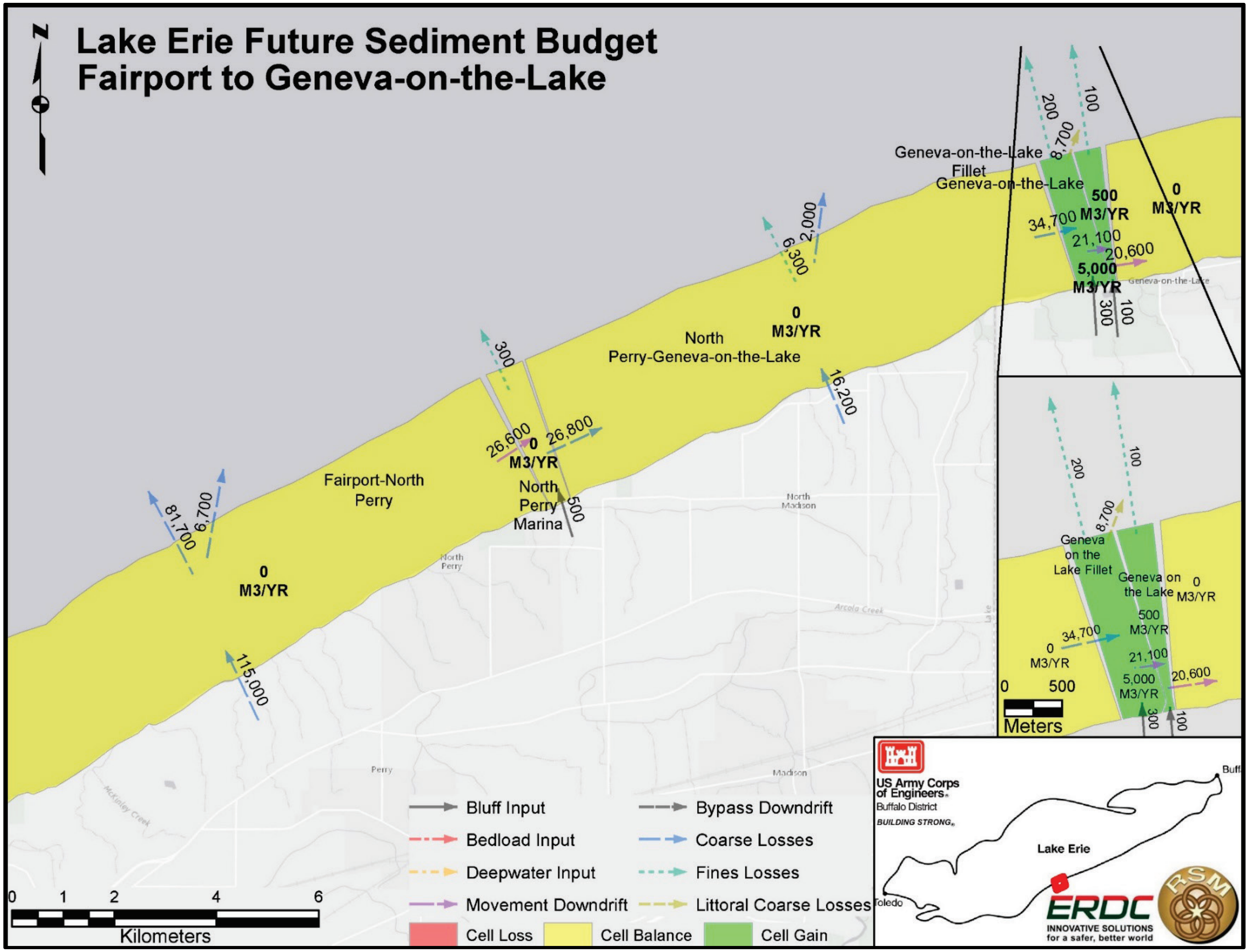


Figure B-33. Geneva-on-the-Lake to Conneaut Pre-Armoring Sediment Budget.

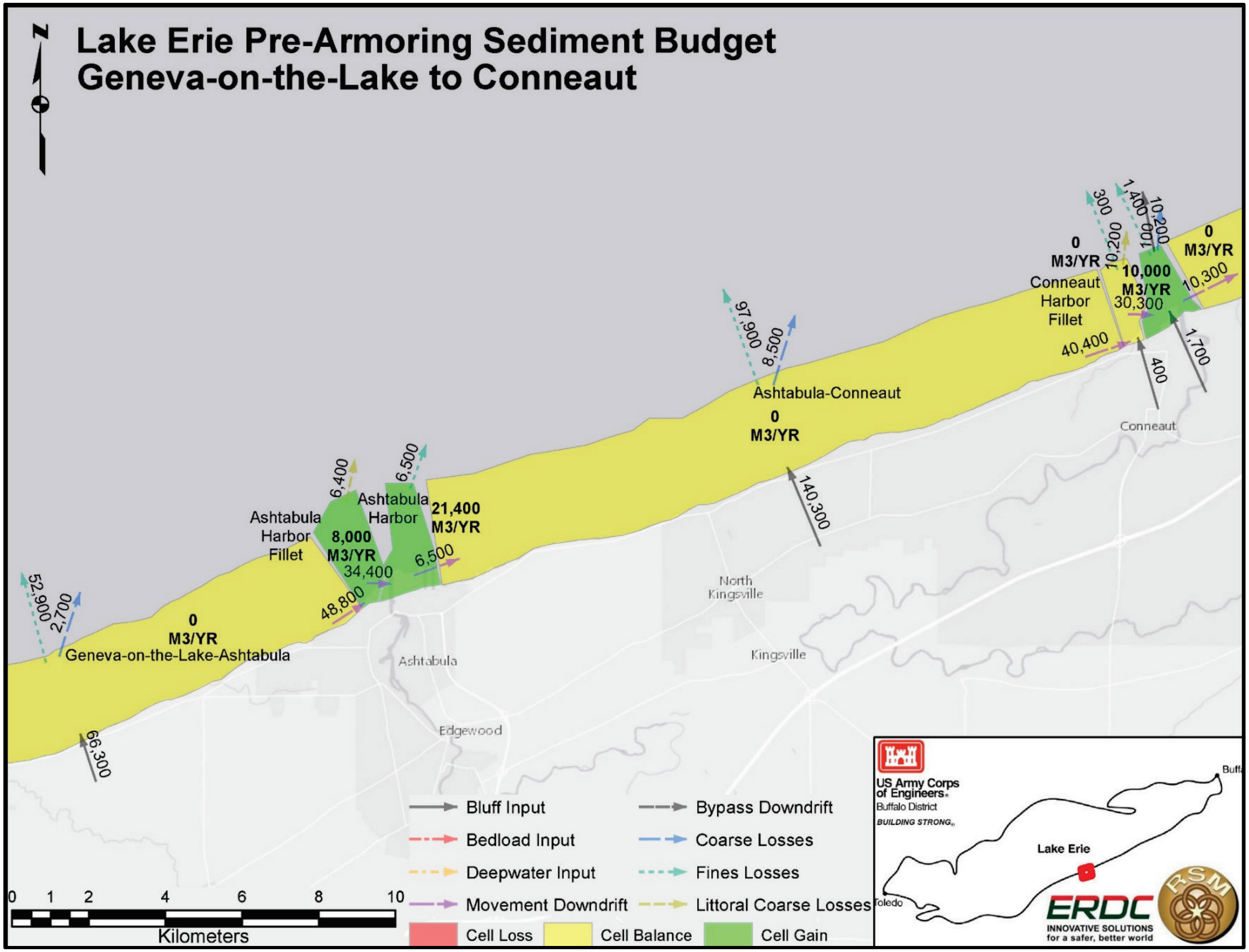


Figure B-34. Geneva-on-the-Lake to Conneaut Mid-Century Sediment Budget.

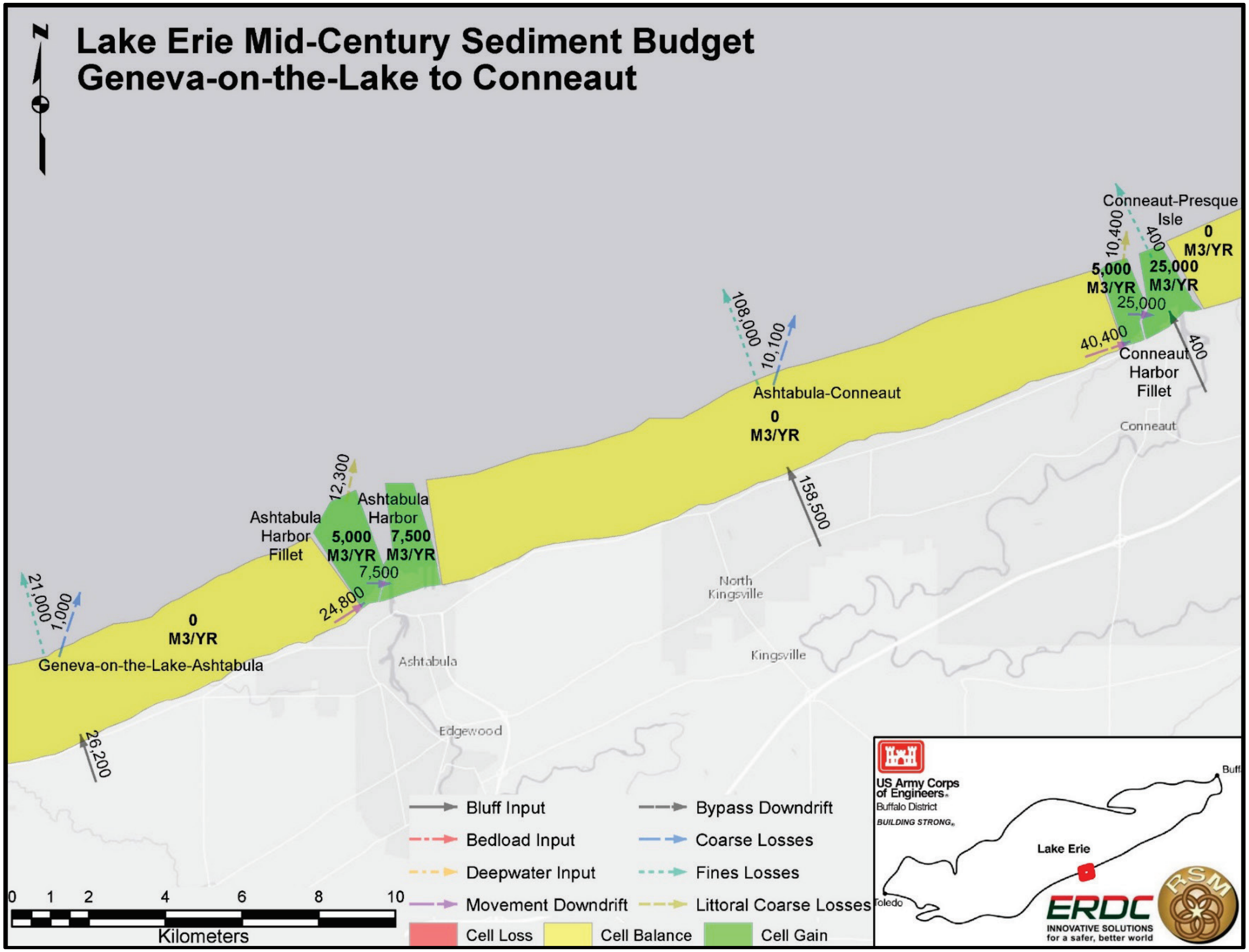


Figure B-35. Geneva-on-the-Lake to Conneaut Recent Sediment Budget.

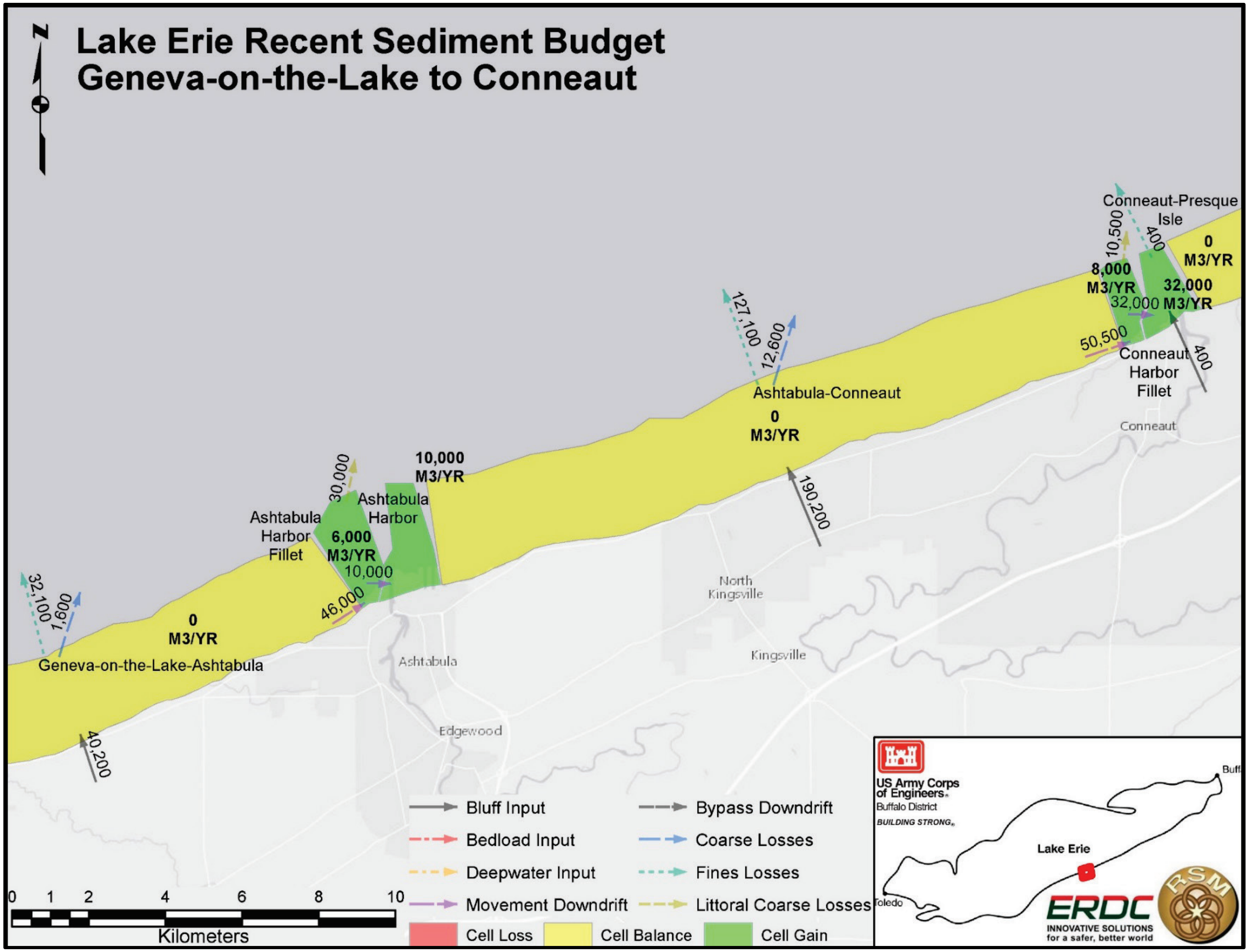


Figure B-36. Geneva-on-the-Lake to Conneaut Future Sediment Budget.

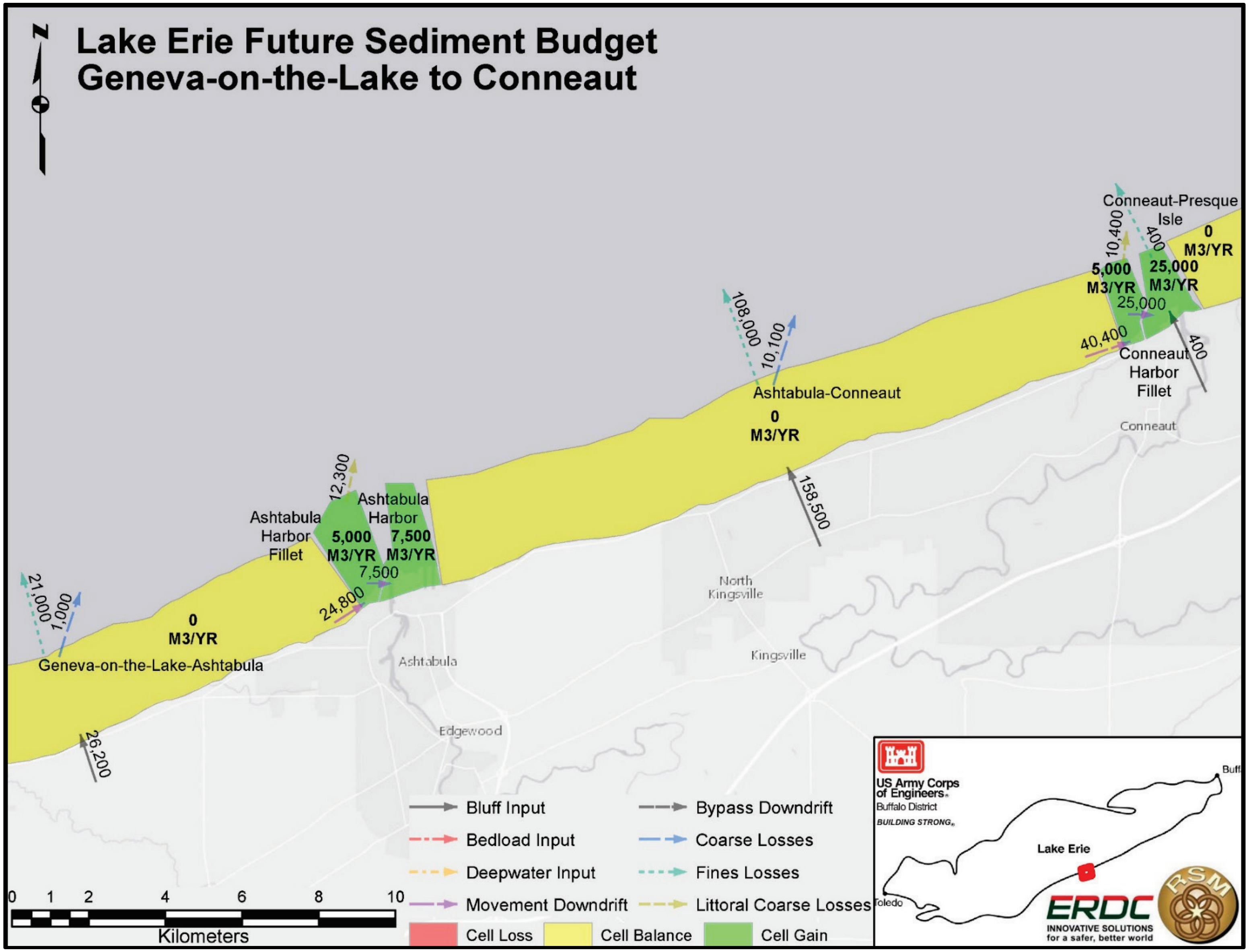


Figure B-37. Conneaut to Presque Isle Pre-Armoring sediment budget.

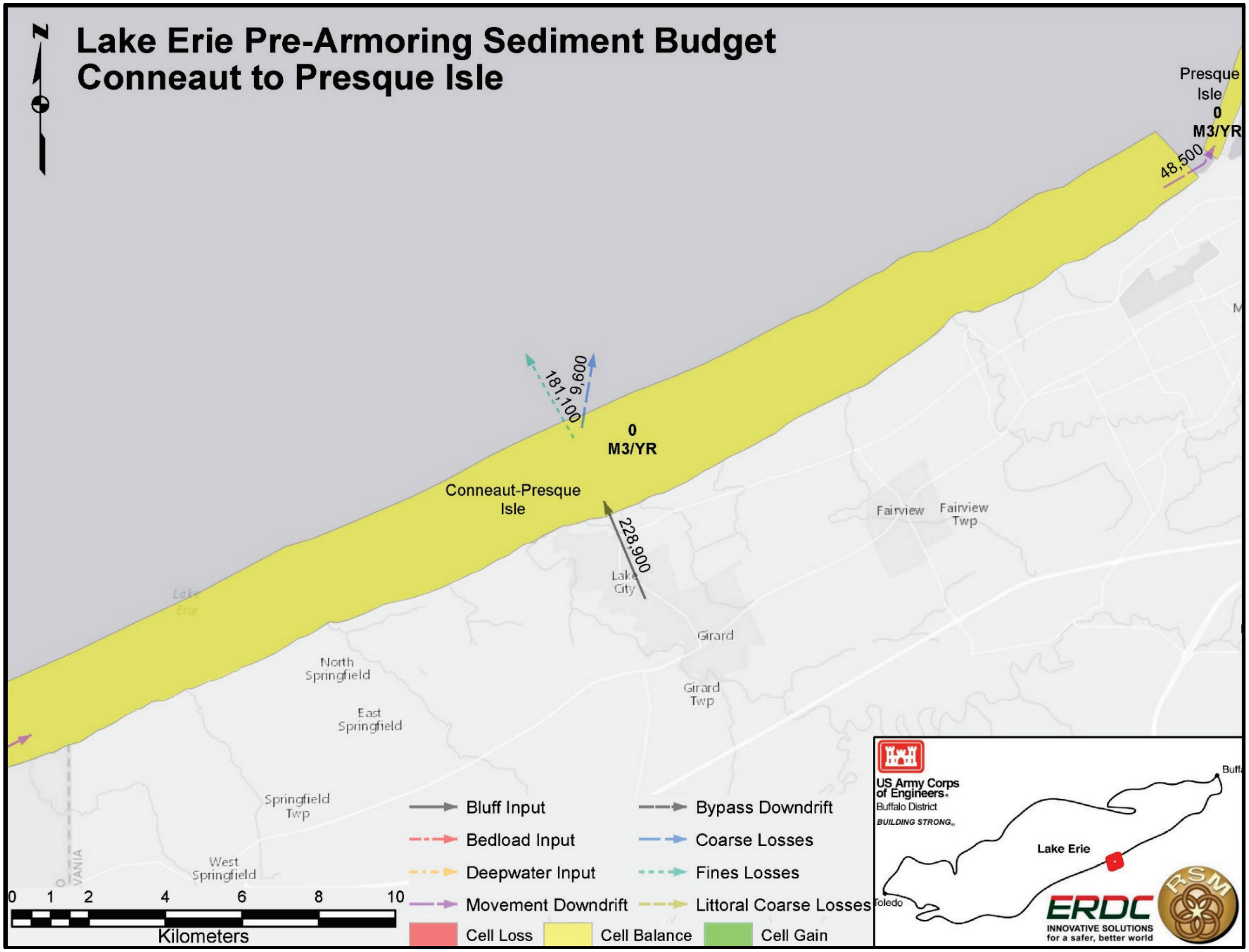


Figure B-38. Conneaut to Presque Isle Mid-Century sediment budget.

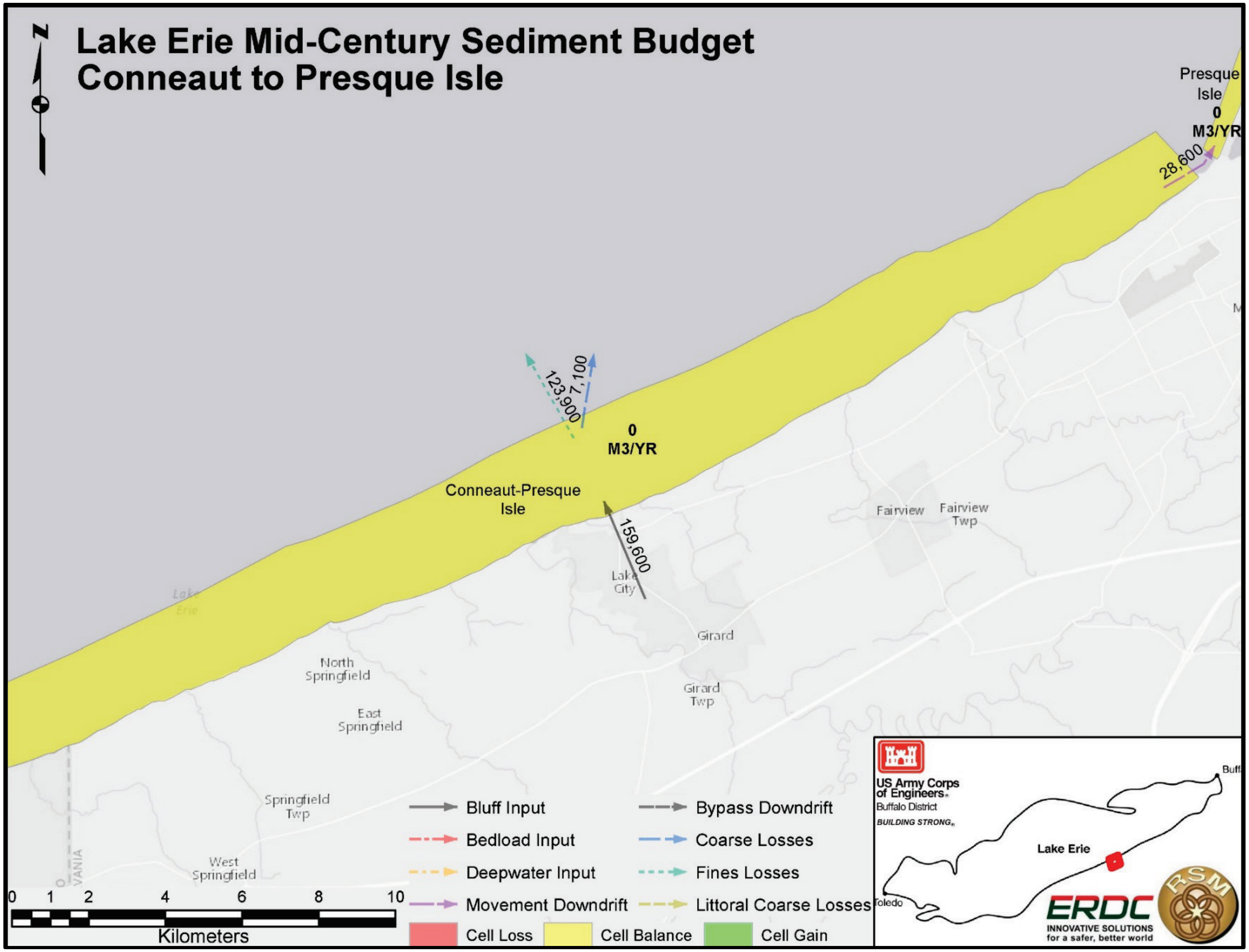


Figure B-39. Conneaut to Presque Isle Recent sediment budget.

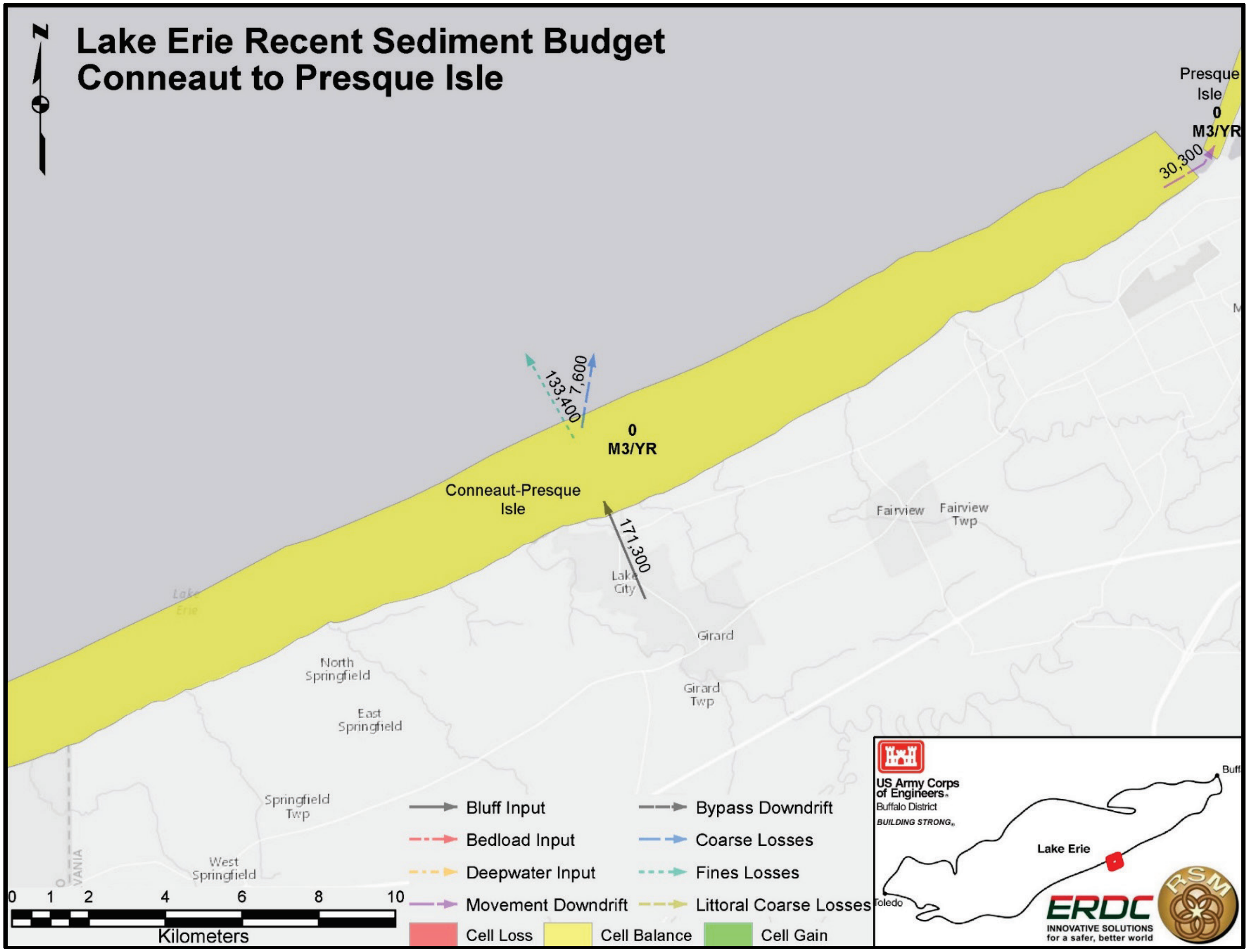


Figure B-40. Conneaut to Presque Isle Future sediment budget.

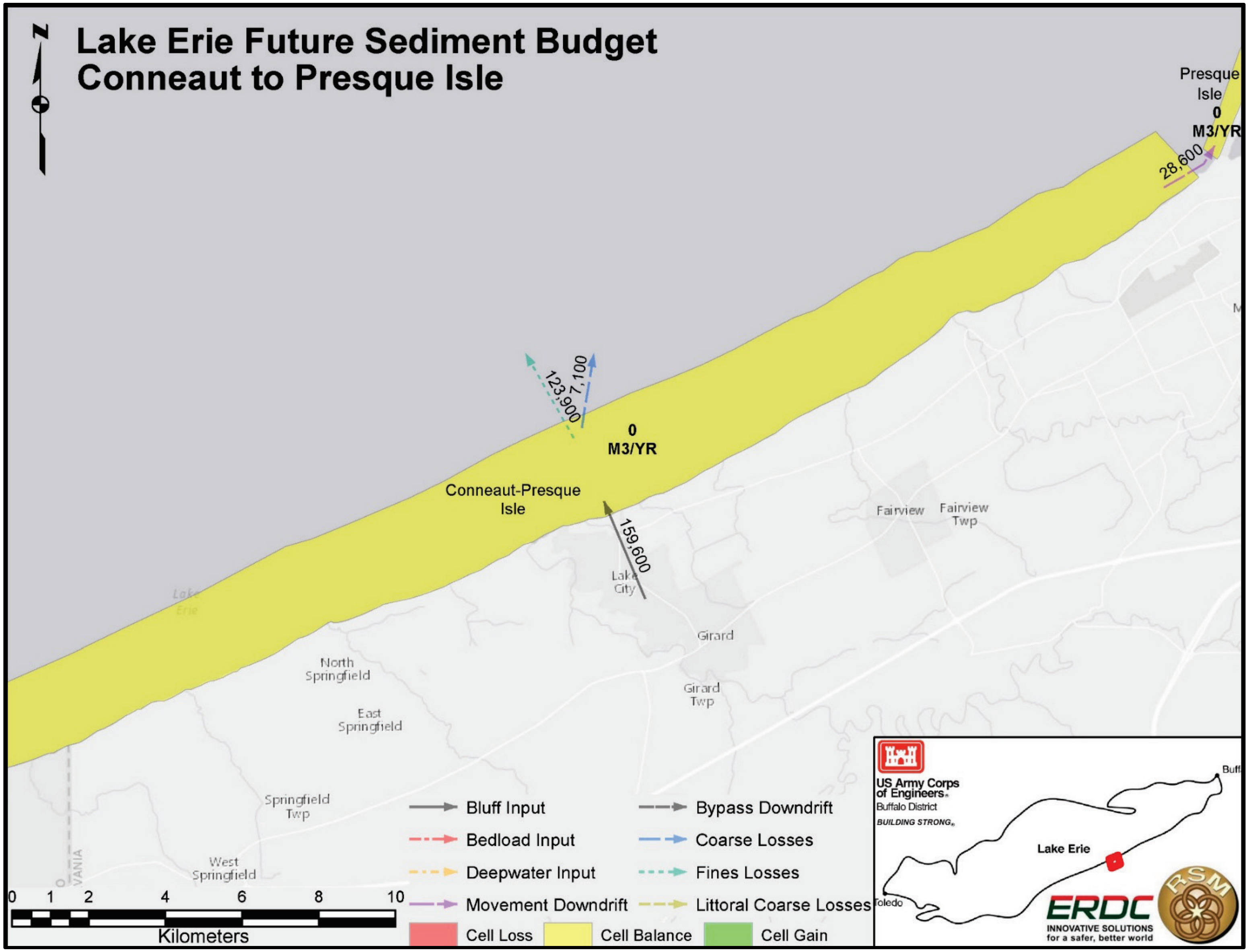


Figure B-41. Presque Isle to North East Pre-Armoring sediment budget.

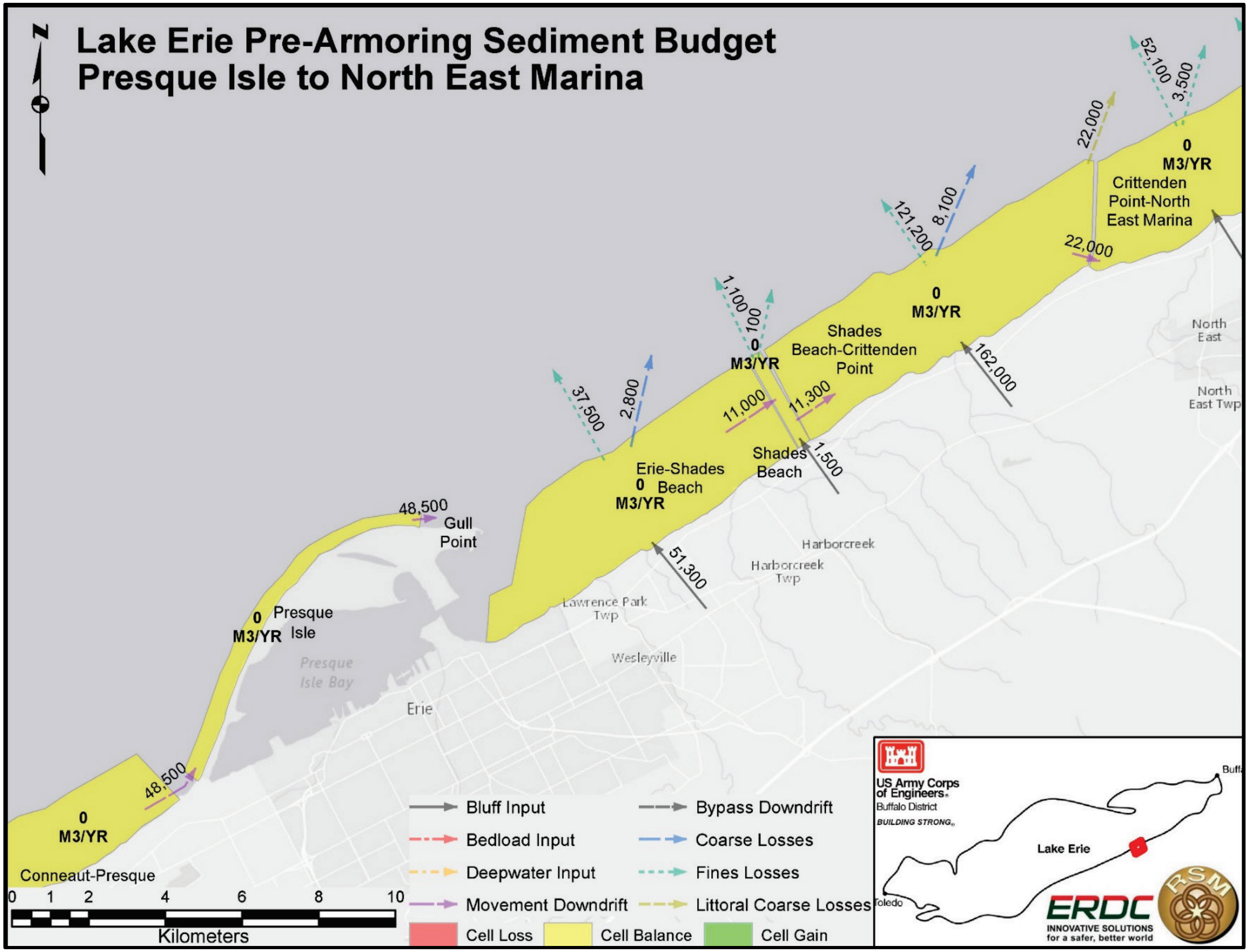


Figure B-42. Presque Isle to North East Mid-Century sediment budget.

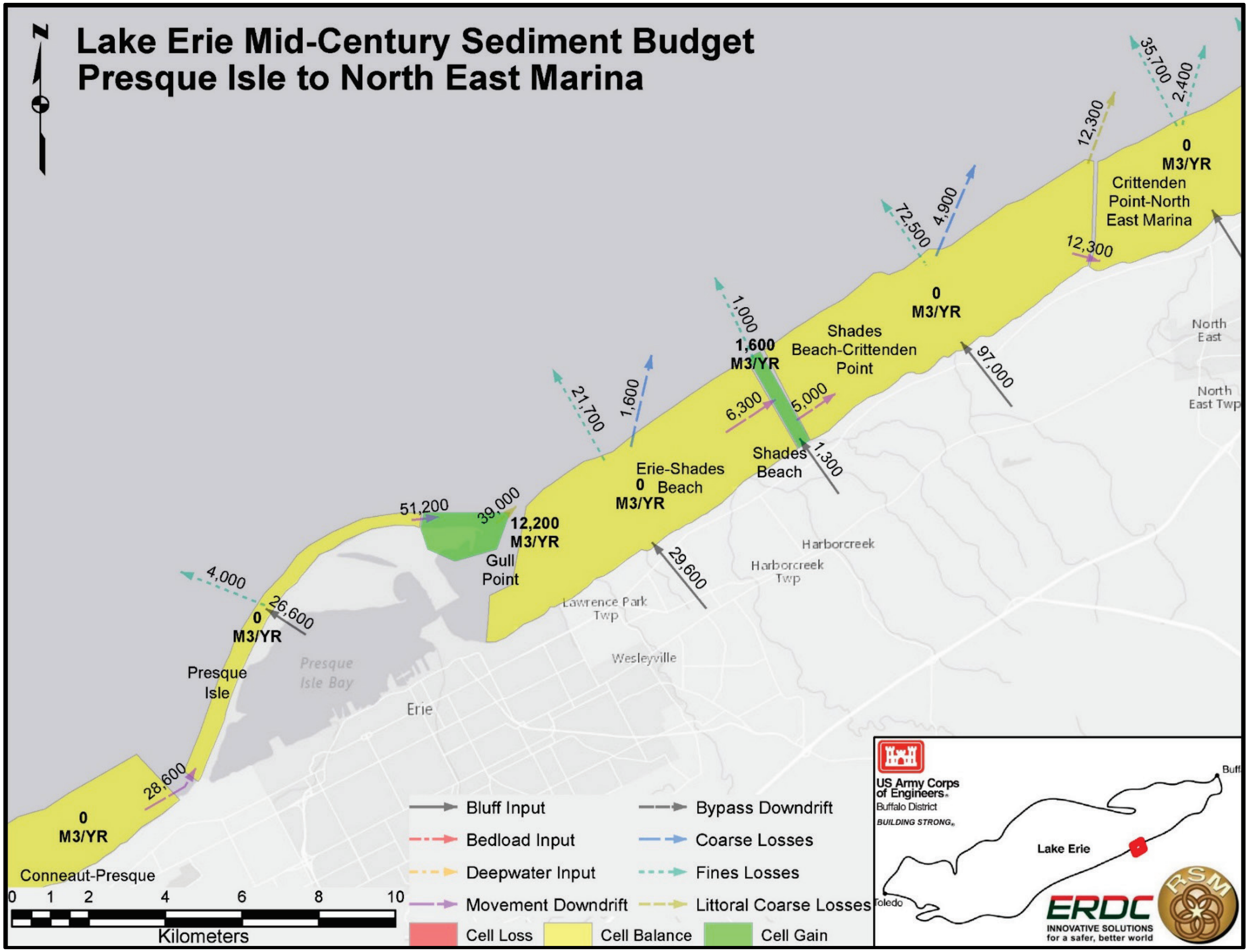


Figure B-43. Presque Isle to North East Recent sediment budget.

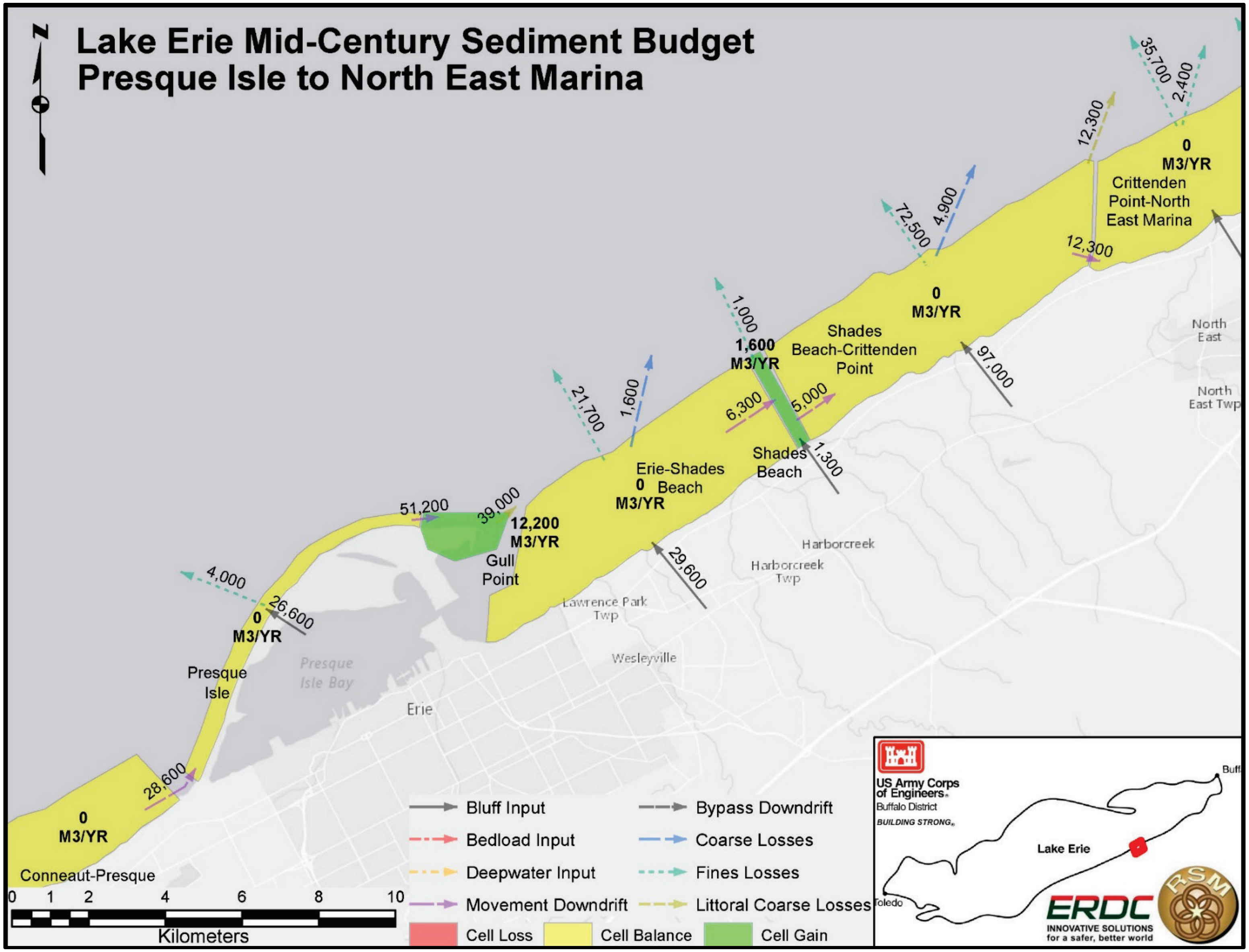


Figure B-44. Presque Isle to North East Future sediment budget.

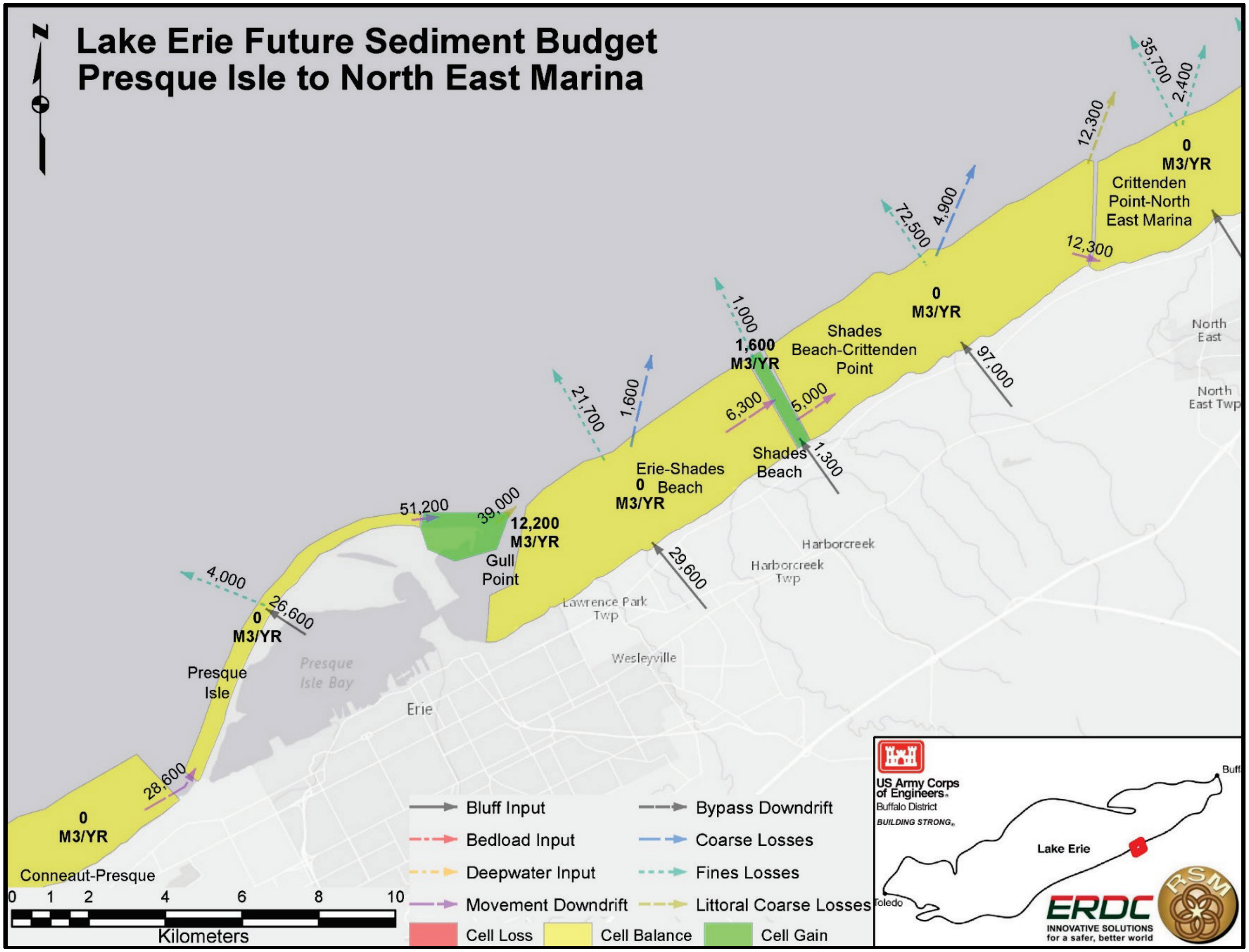


Figure B-45. North East to Barcelona Pre-Armoring sediment budget.

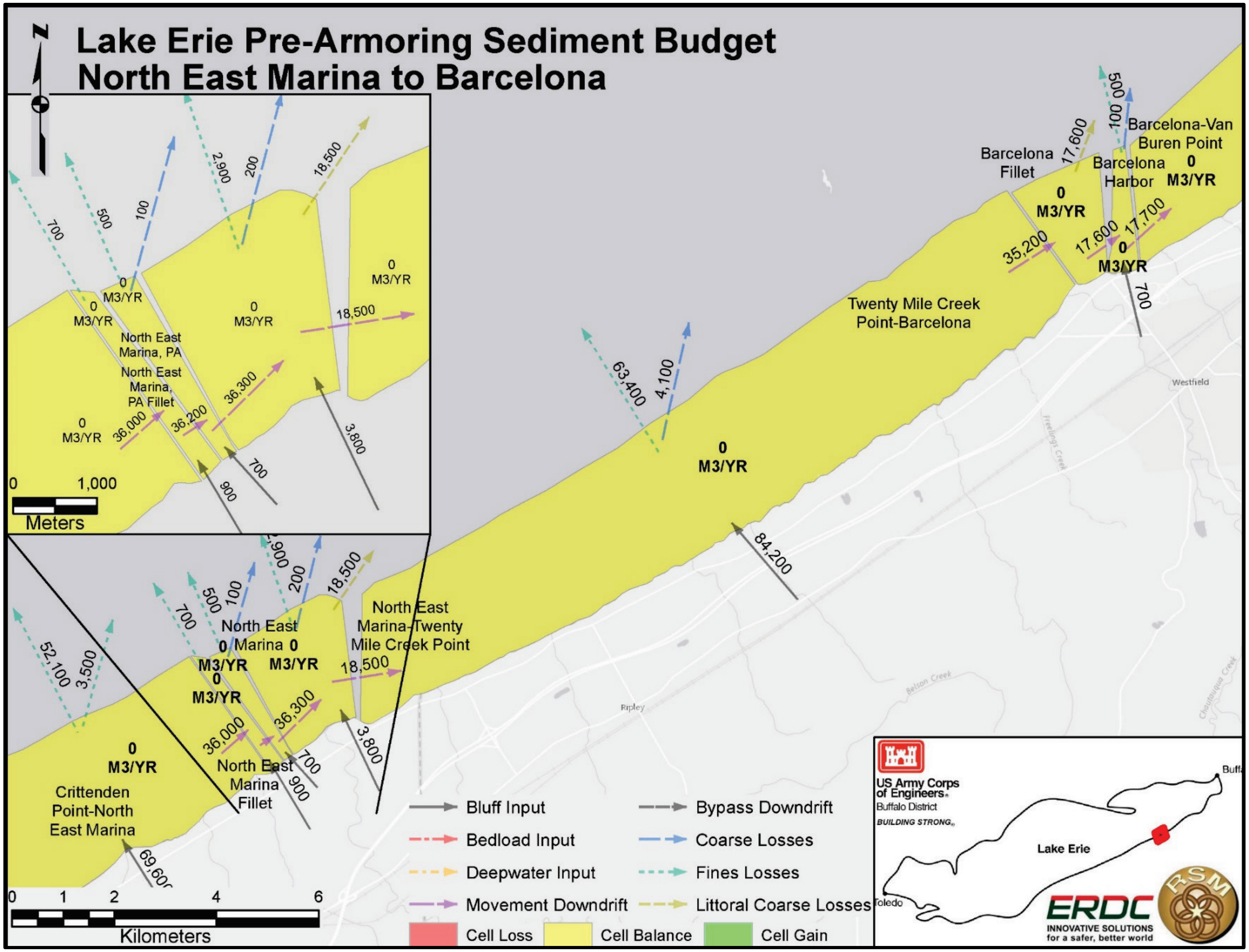


Figure B-46. North East to Barcelona Mid-Century sediment budget.

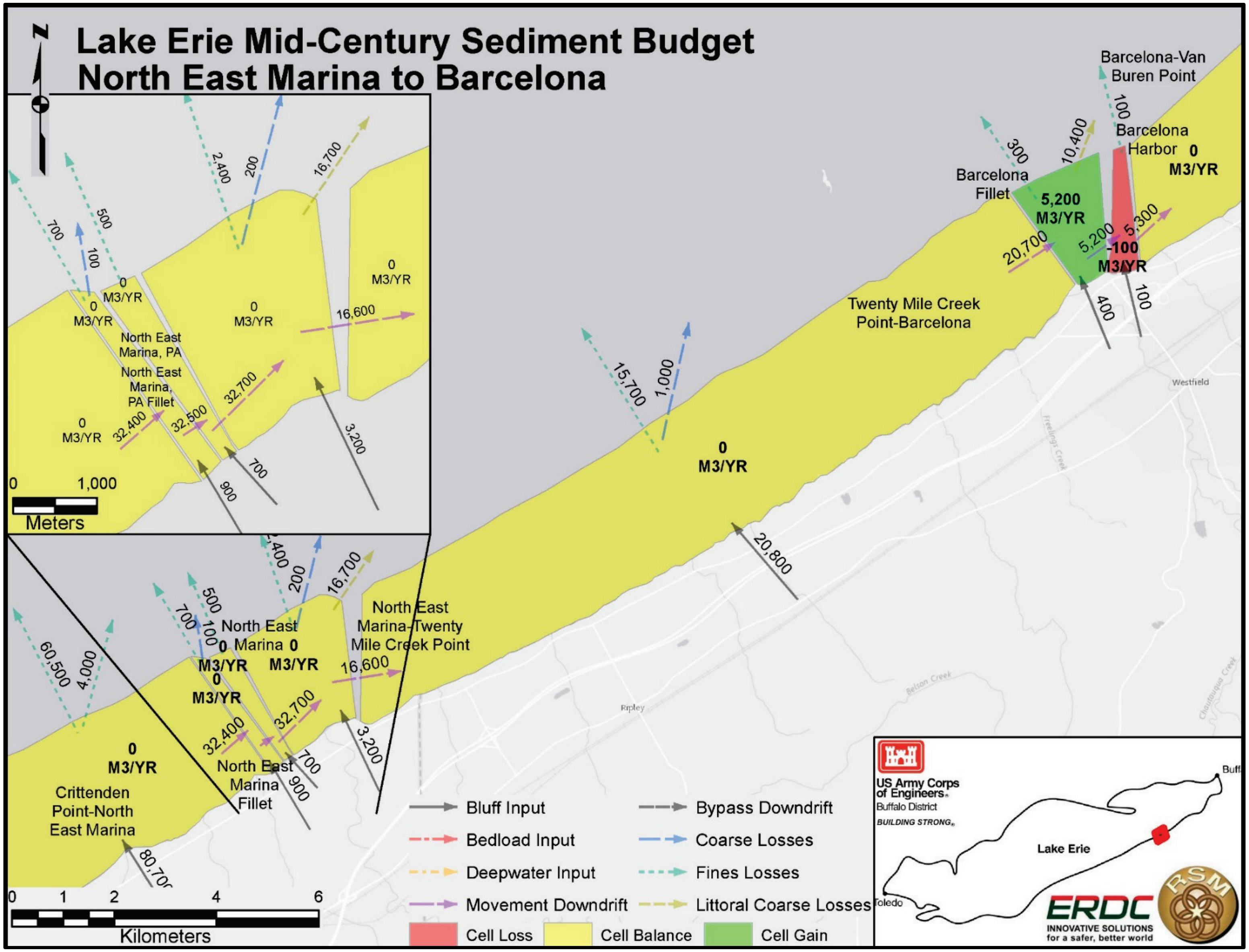


Figure B-47. North East to Barcelona Recent sediment budget.

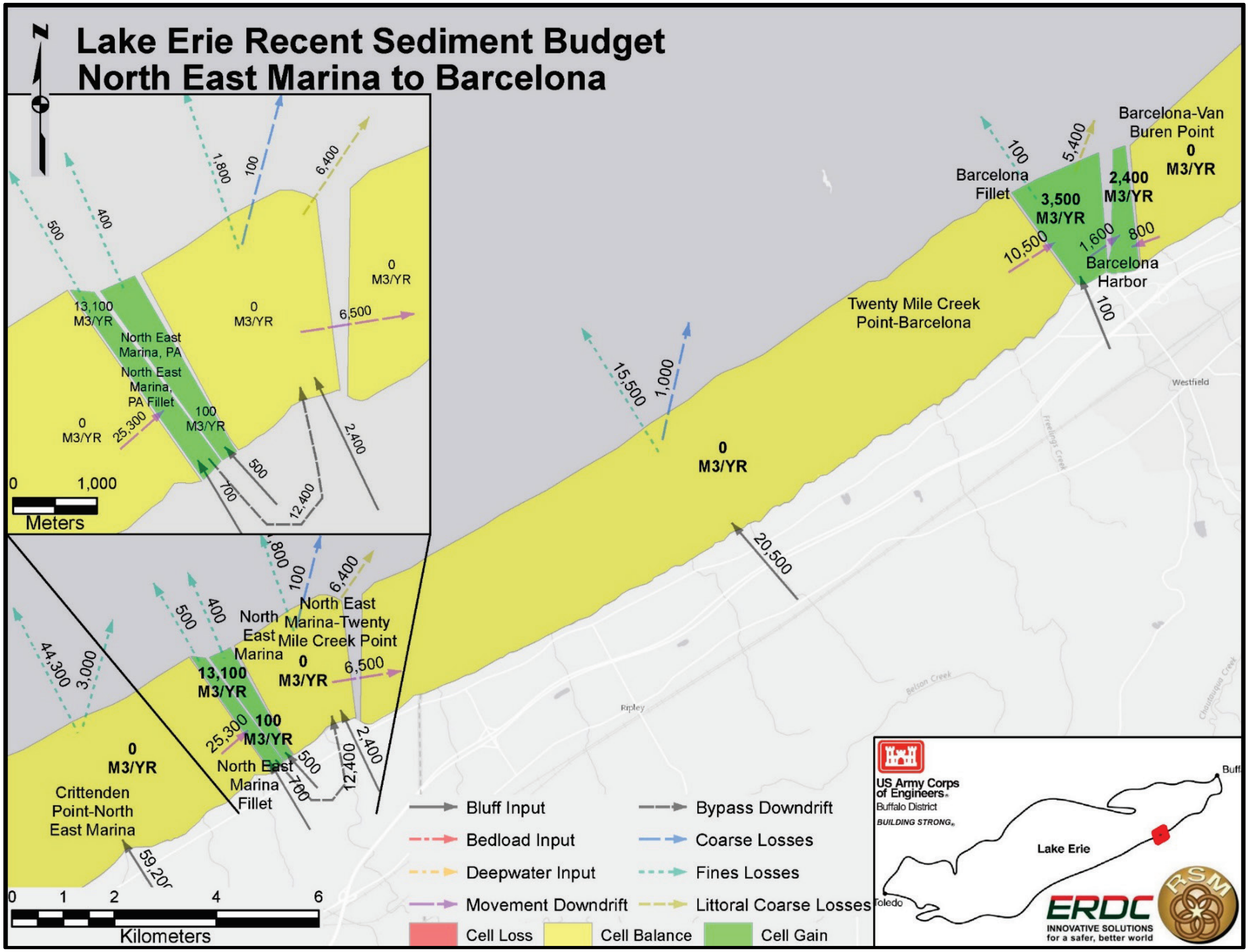


Figure B-48. Northeast to Barcelona Future sediment budget.

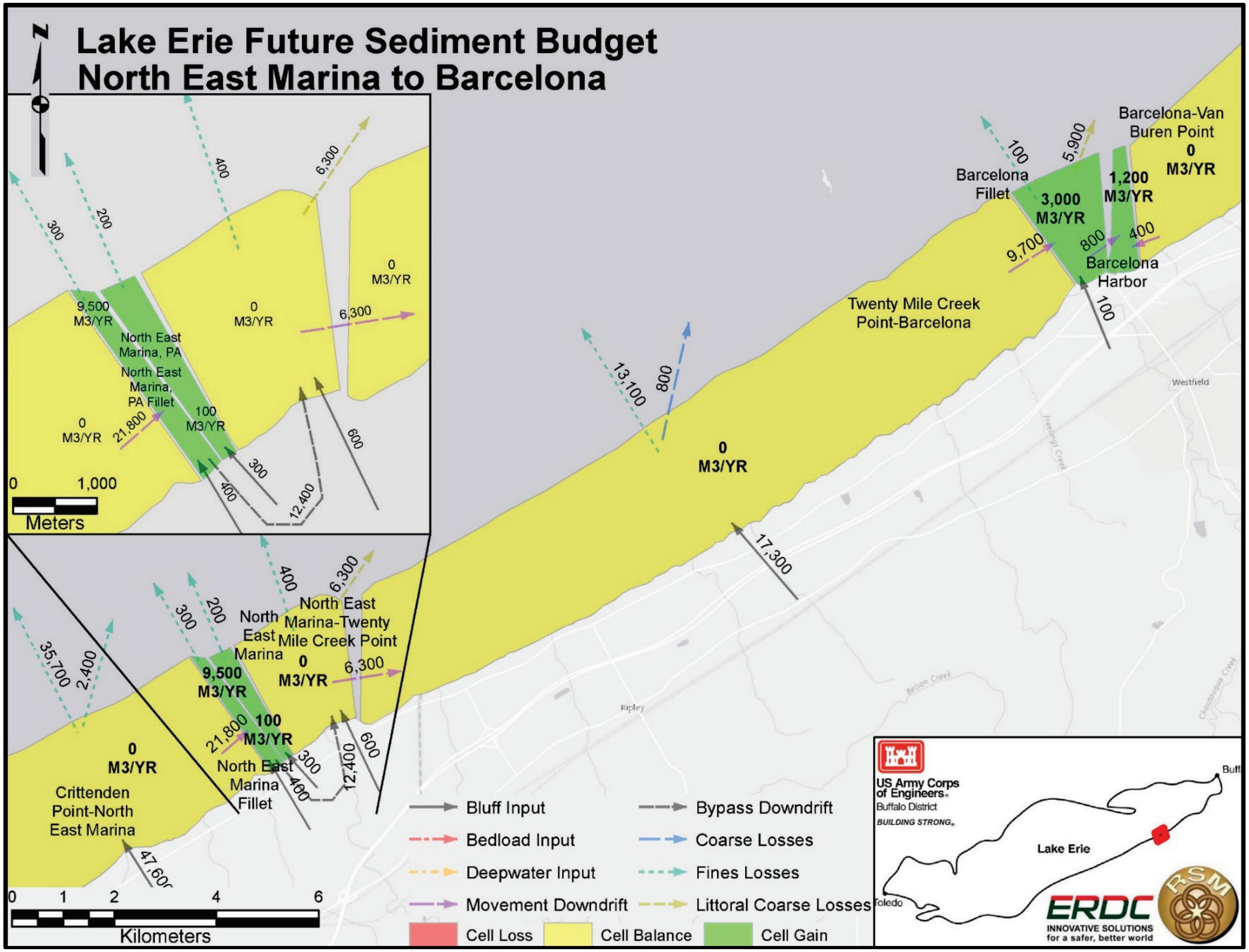


Figure B-49. Barcelona to Dunkirk Pre-Armoring sediment budget.

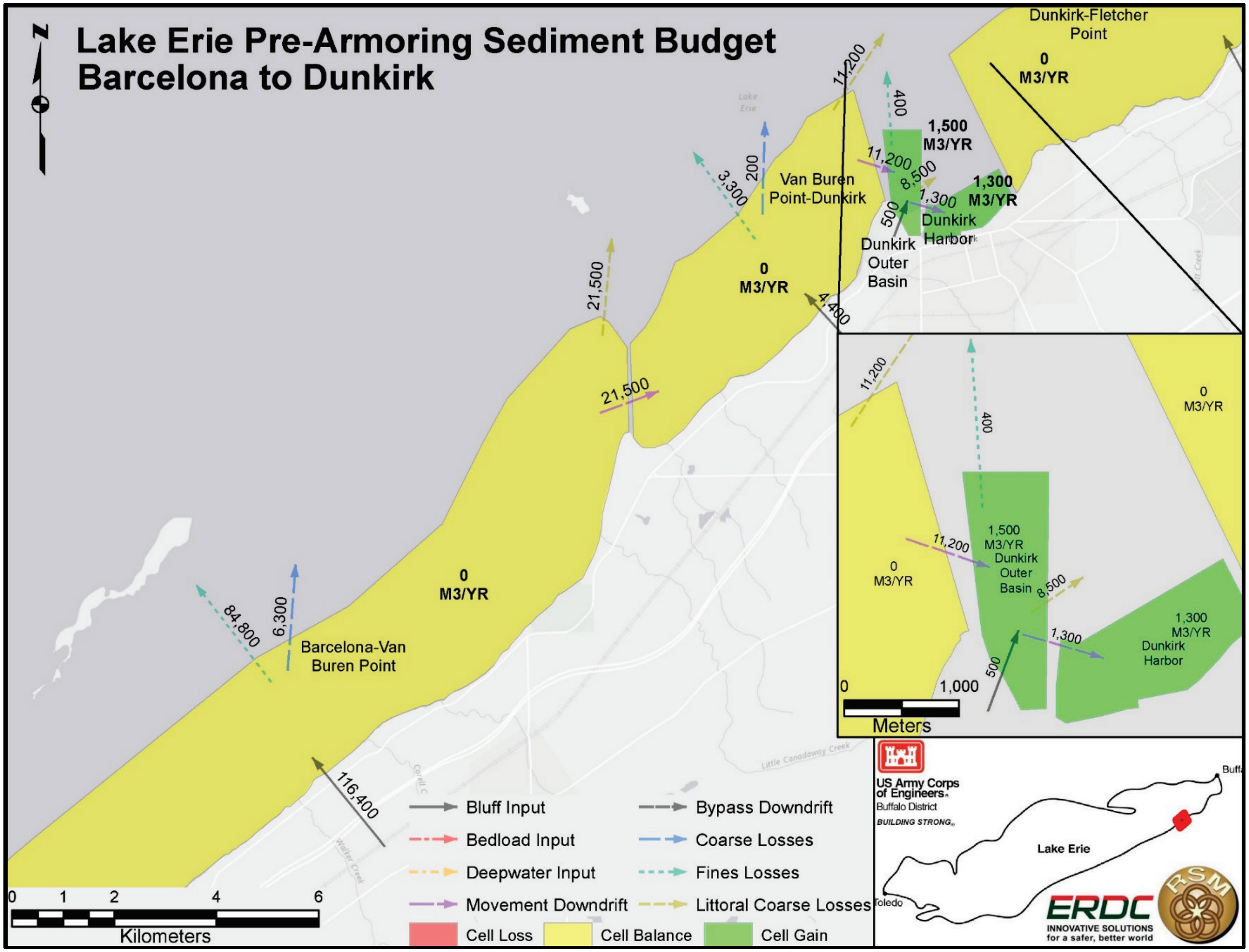


Figure B-50. Barcelona to Dunkirk Mid-Century sediment budget.

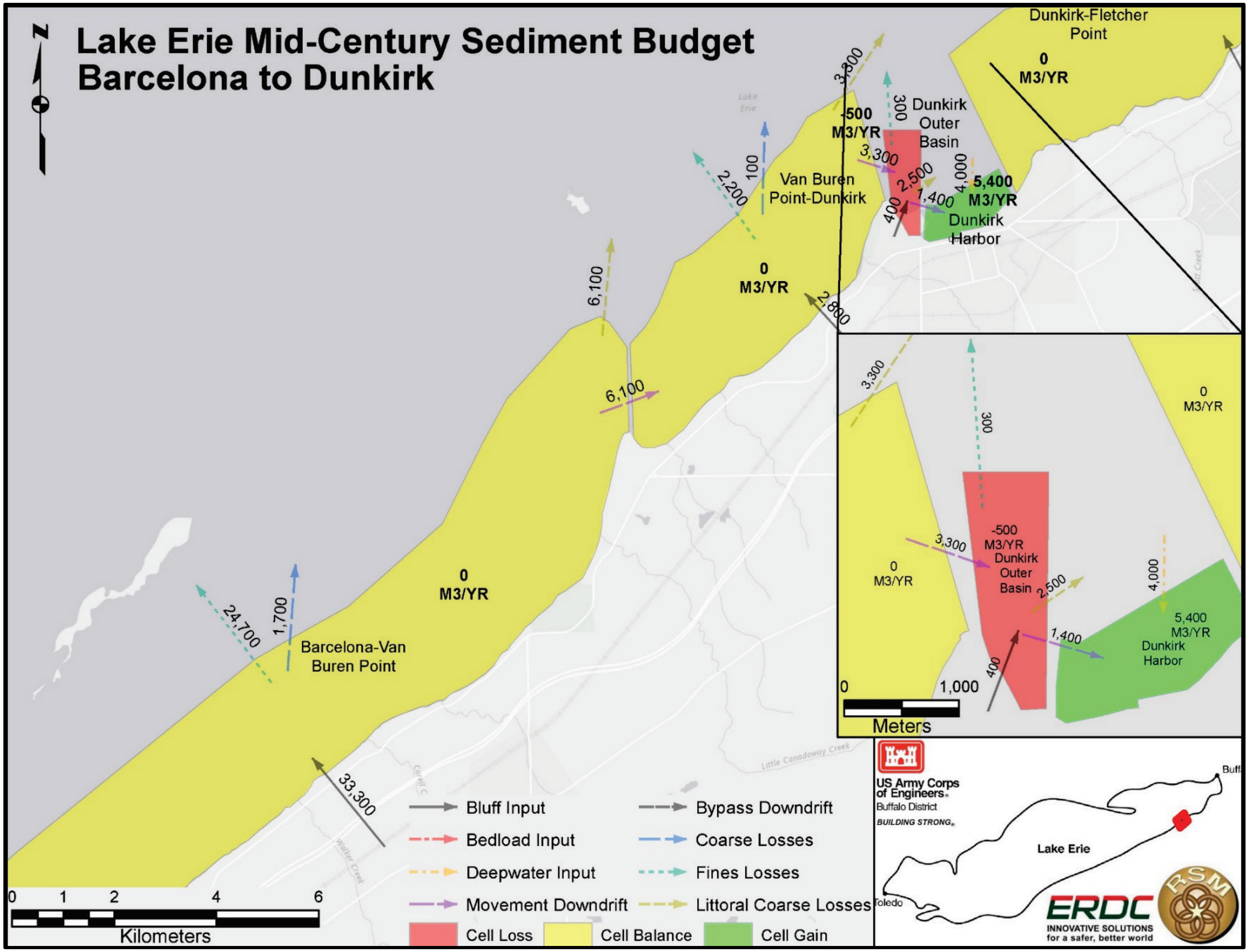


Figure B-51. Barcelona to Dunkirk Recent sediment budget.

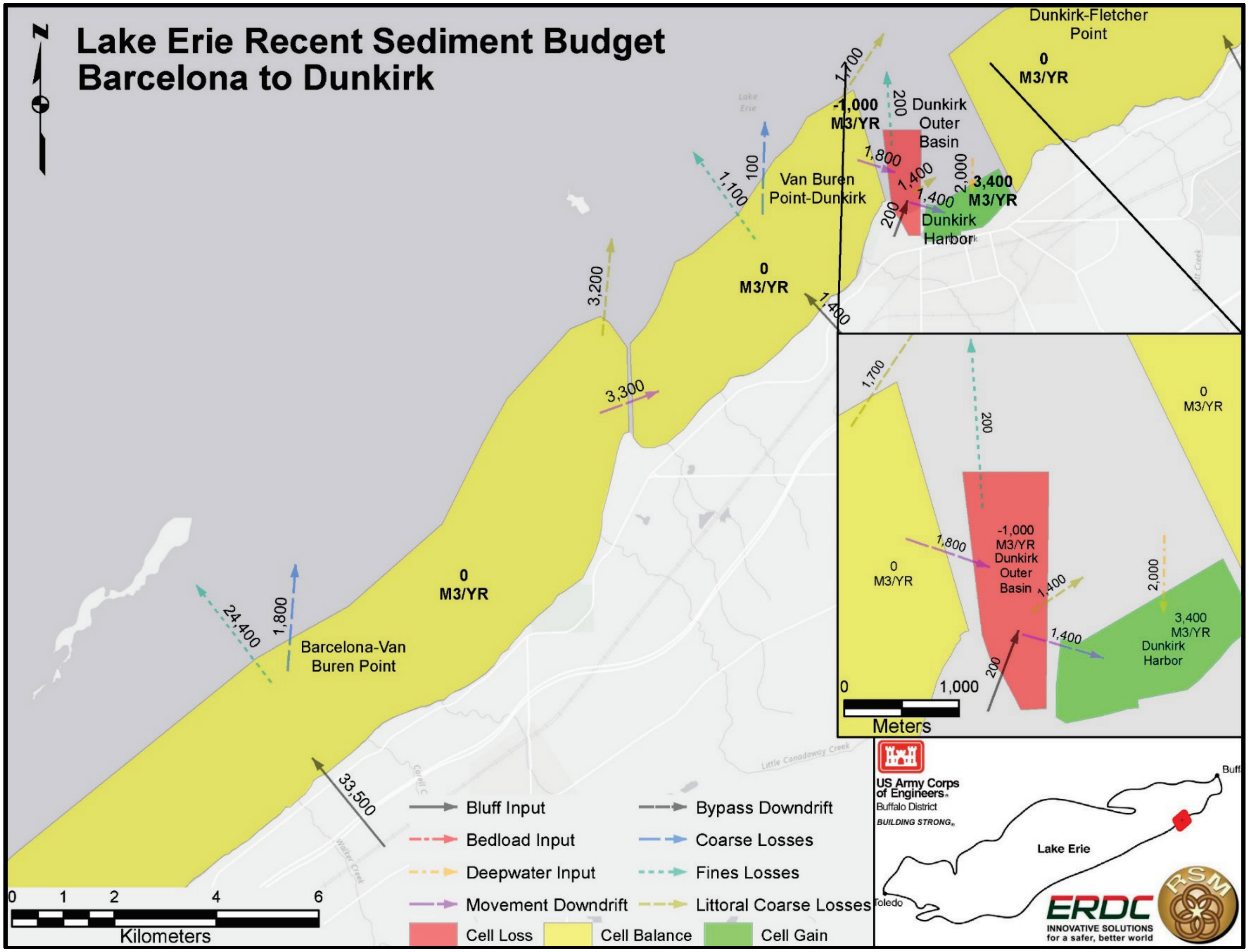


Figure B-52. Barcelona to Dunkirk Future sediment budget.

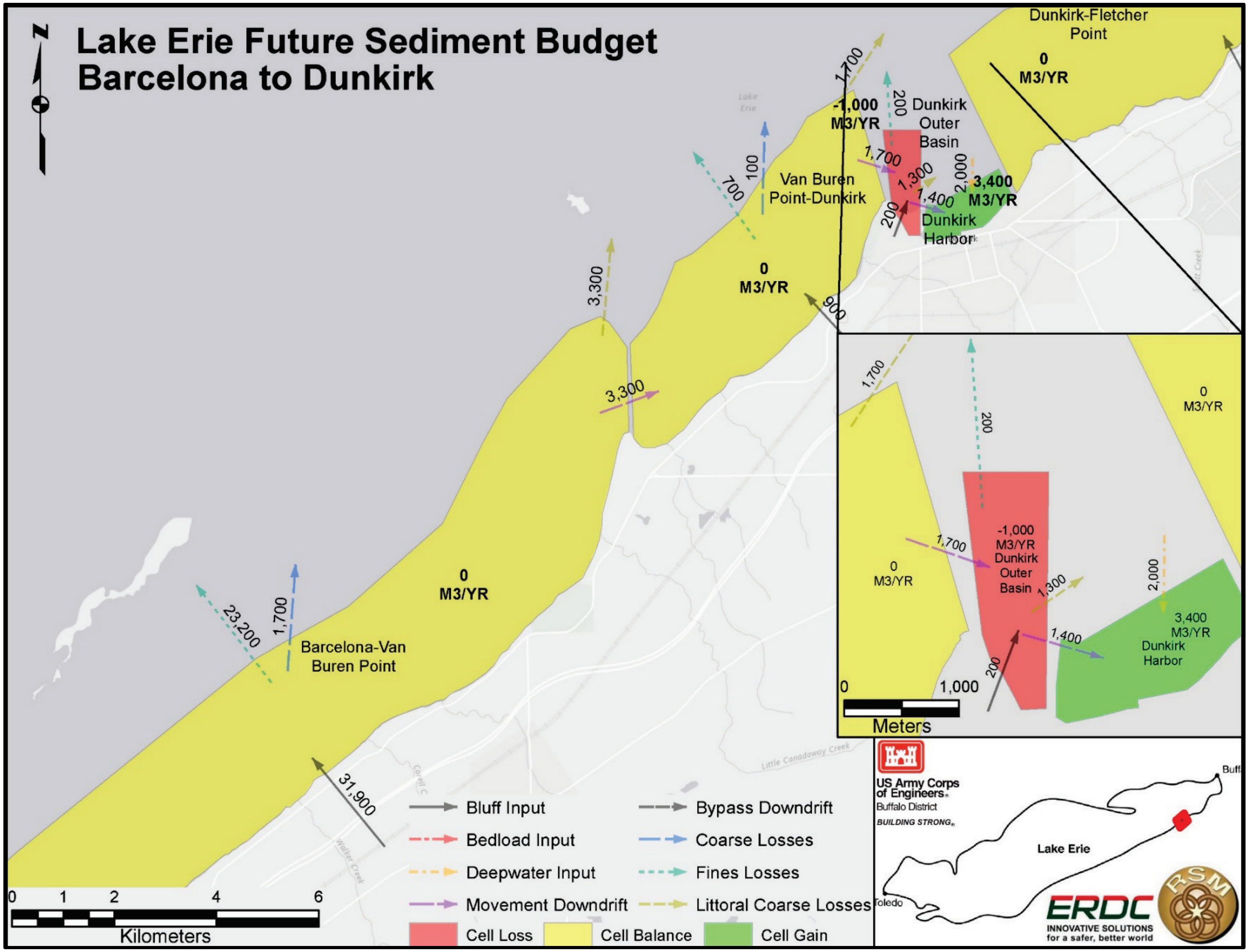


Figure B-53. Dunkirk to Cattaraugus Pre-Armoring sediment budget.

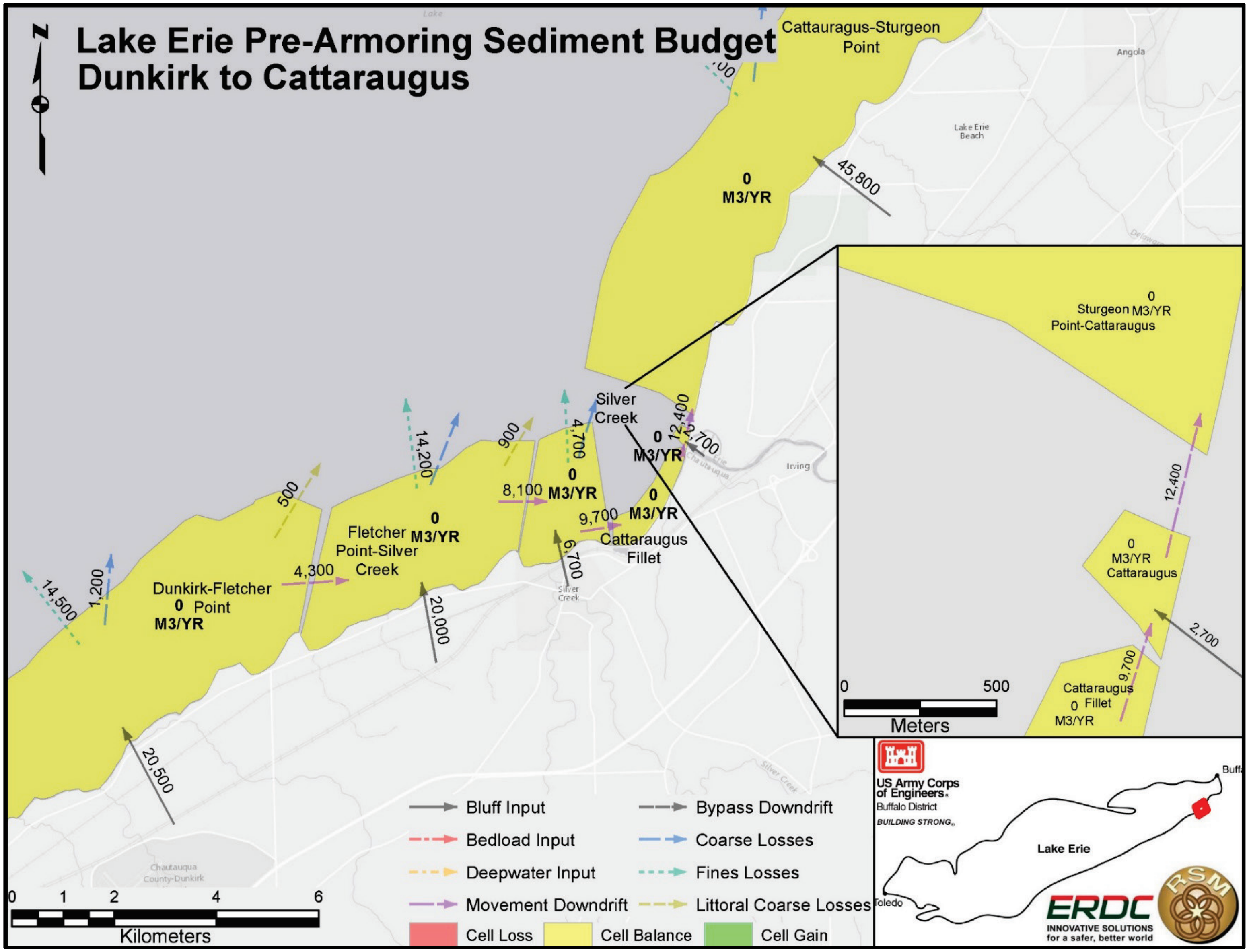


Figure B-54. Dunkirk to Cattaraugus Mid-Century sediment budget.

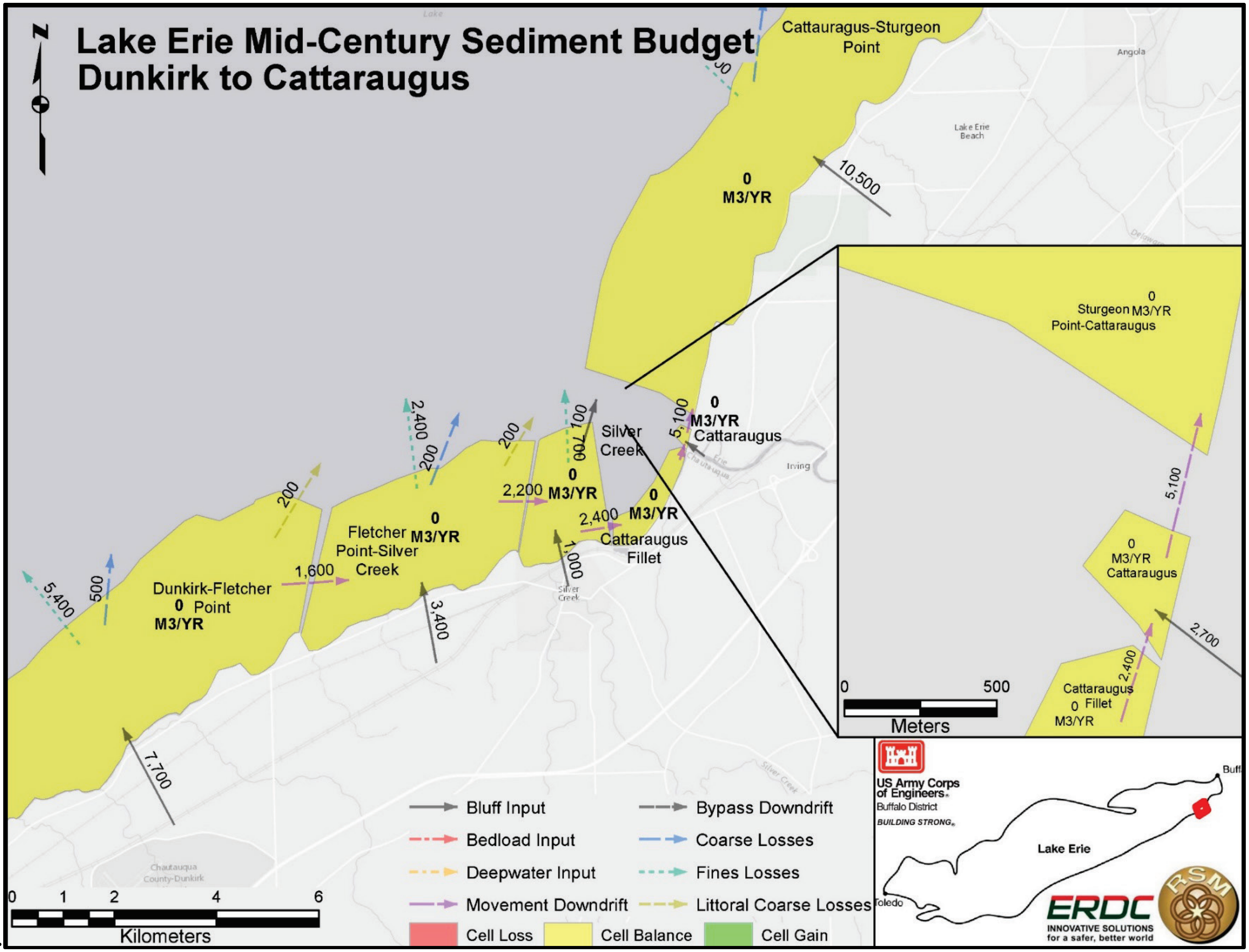


Figure B-55. Dunkirk to Cattaraugus Recent sediment budget.

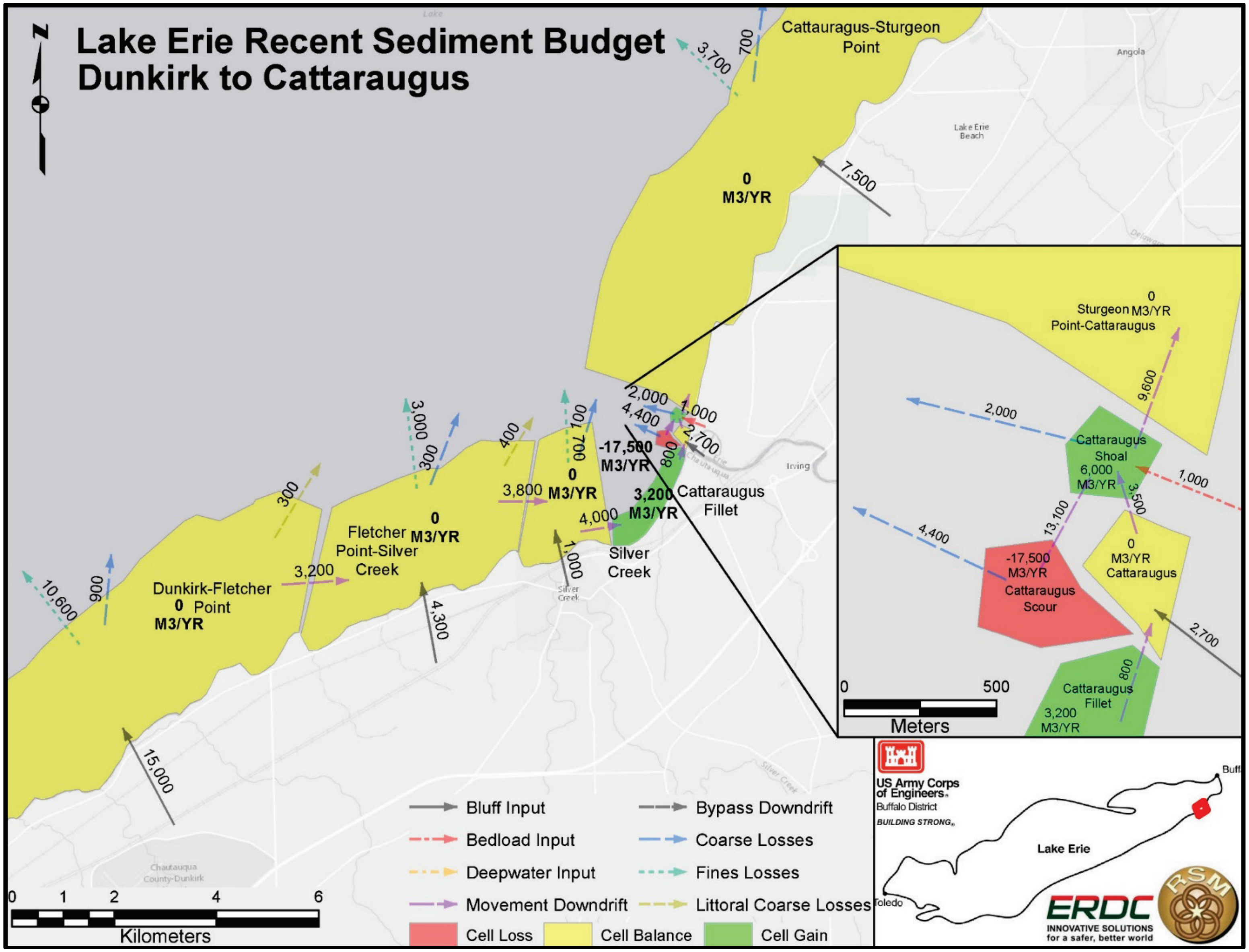


Figure B-56. Dunkirk to Cattaraugus Future sediment budget.

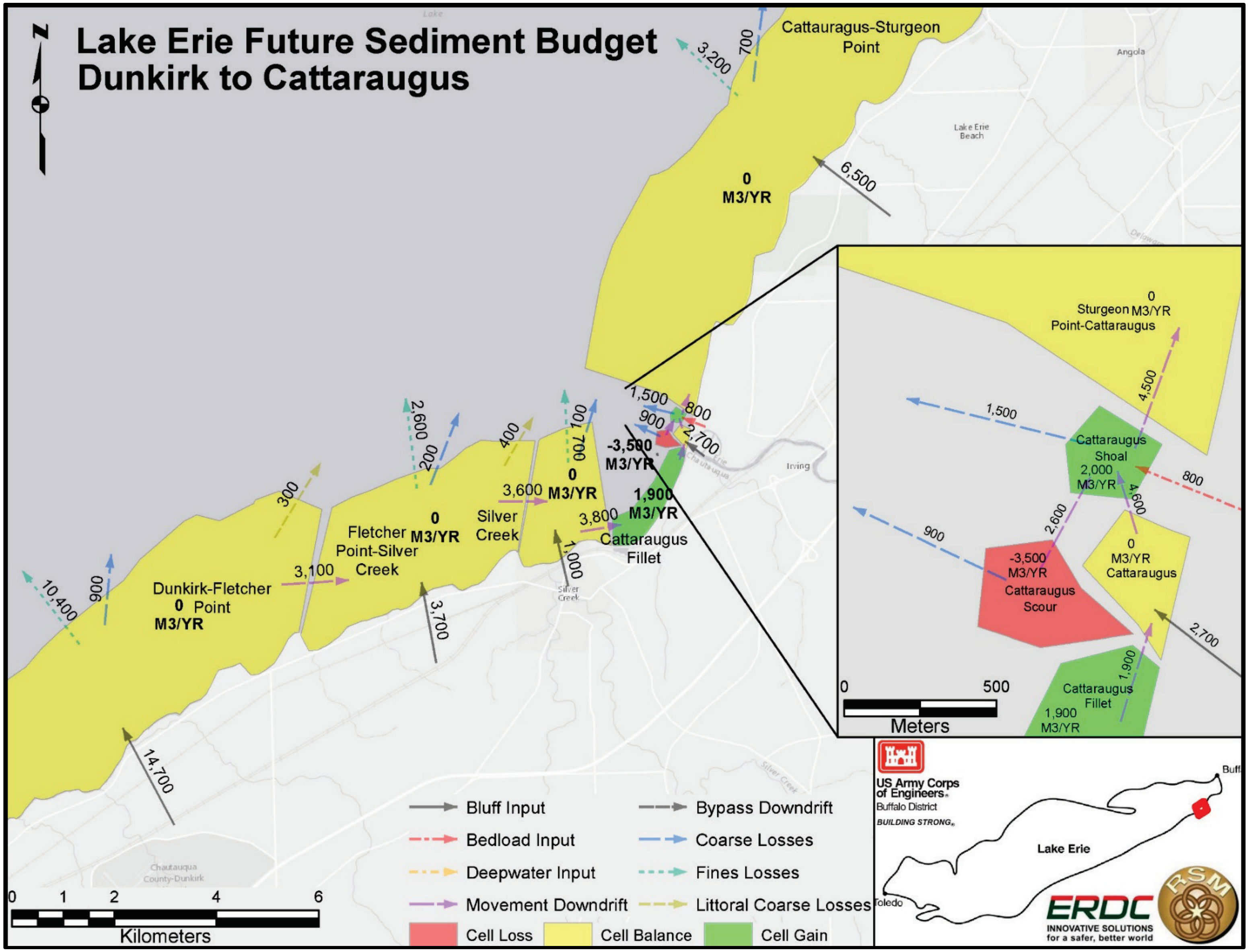


Figure B-57. Cattaraugus to Buffalo Pre-Armoring sediment budget.

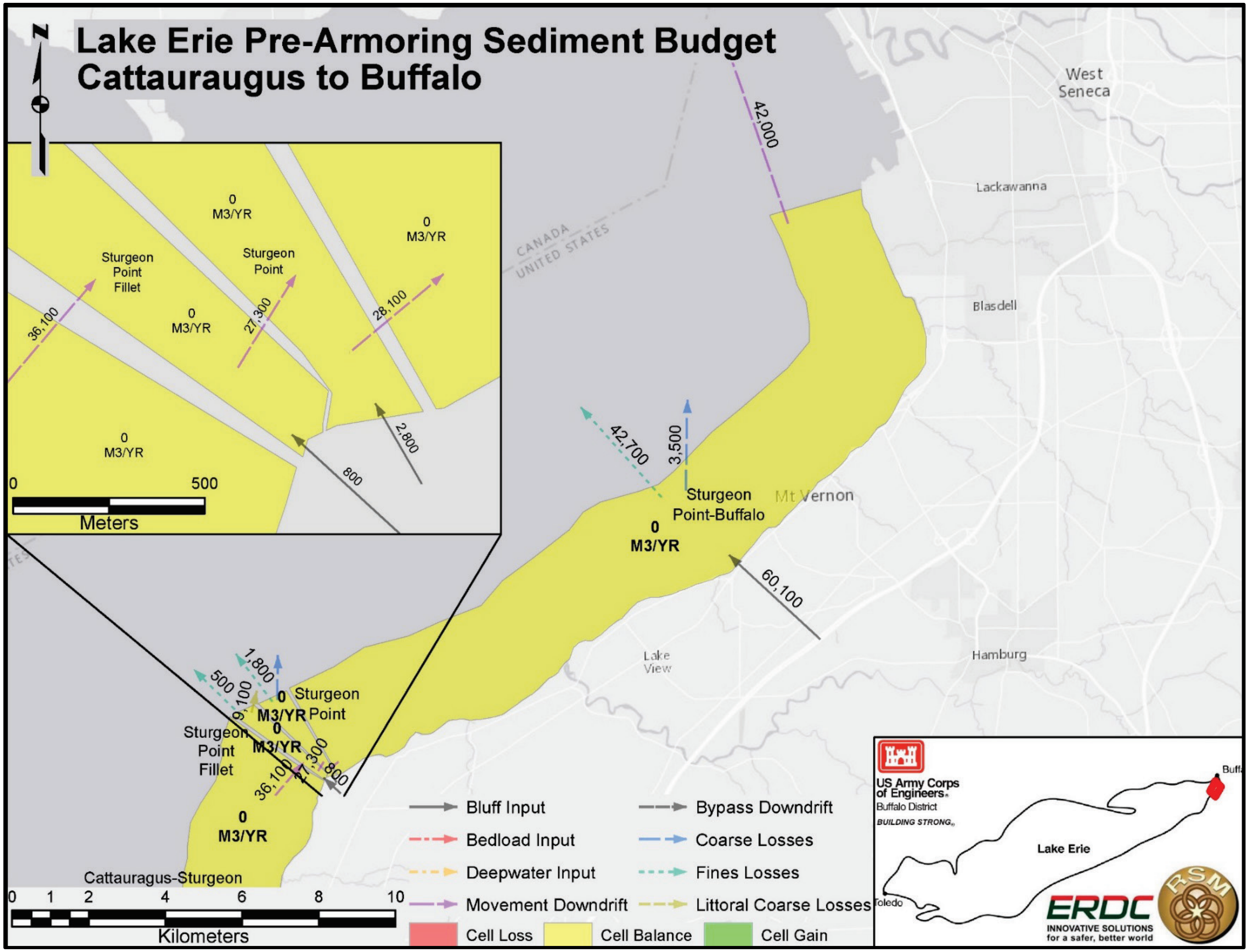


Figure B-58. Cattaraugus to Buffalo Mid-Century sediment budget.

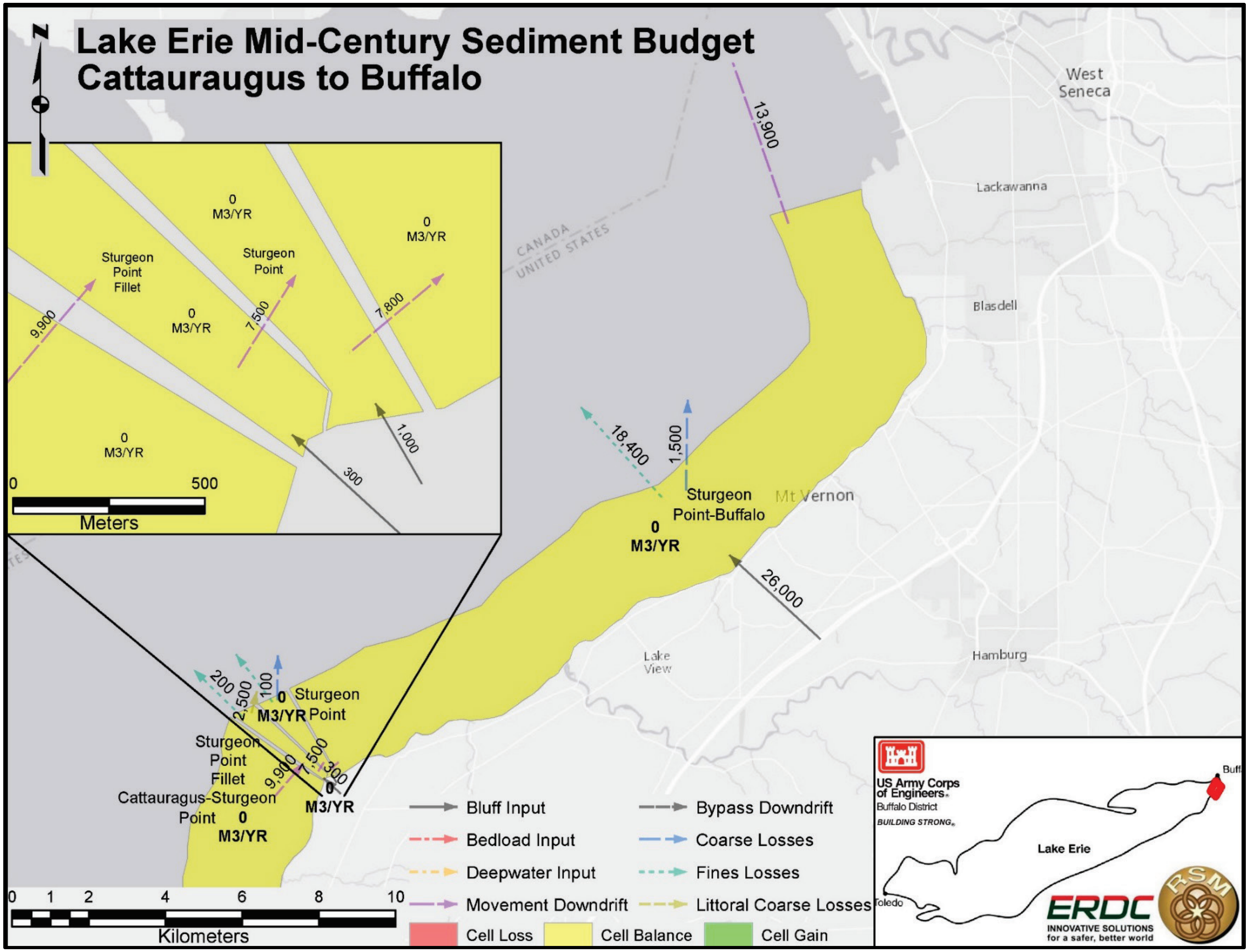


Figure B-59. Cattaraugus to Buffalo Recent sediment budget.

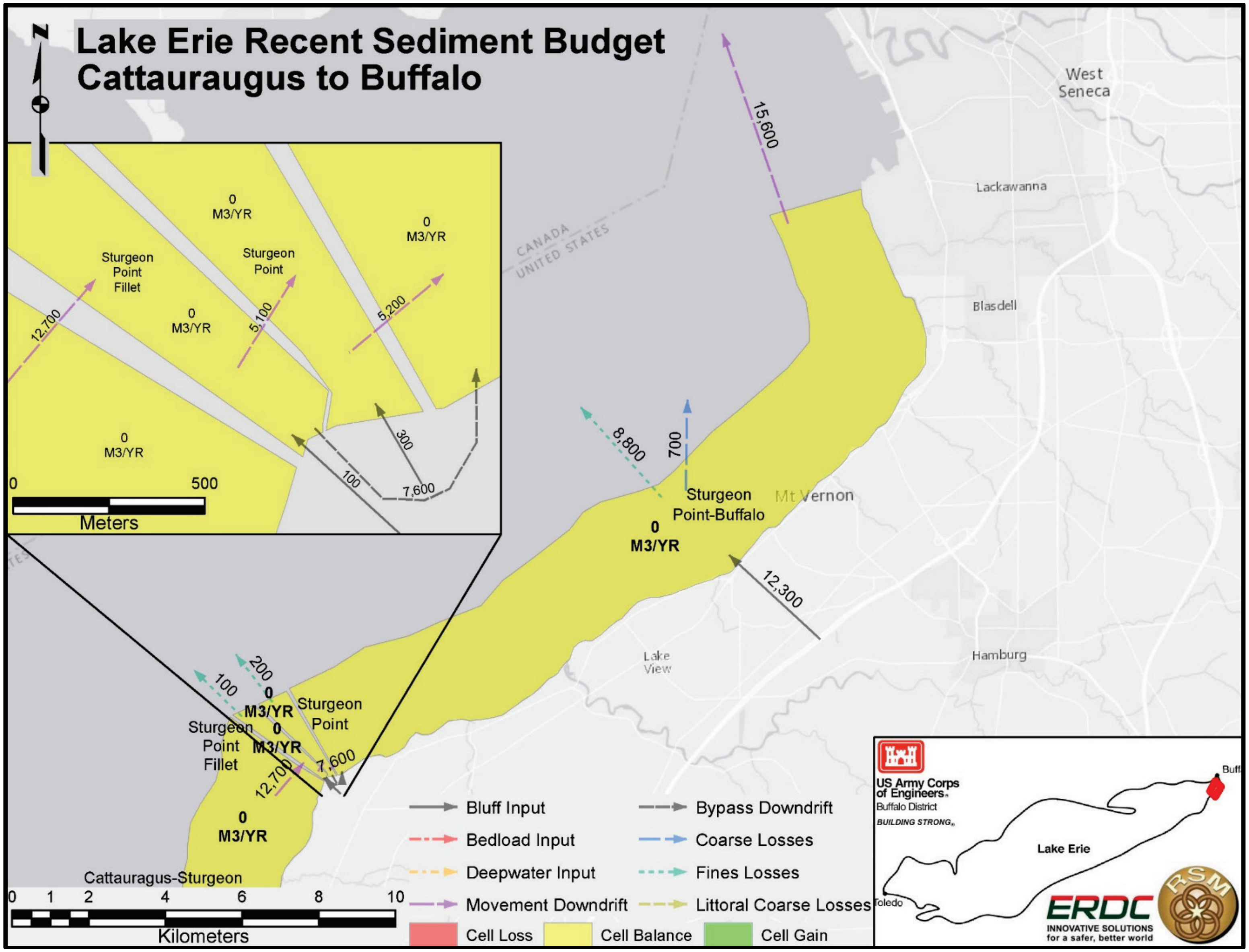
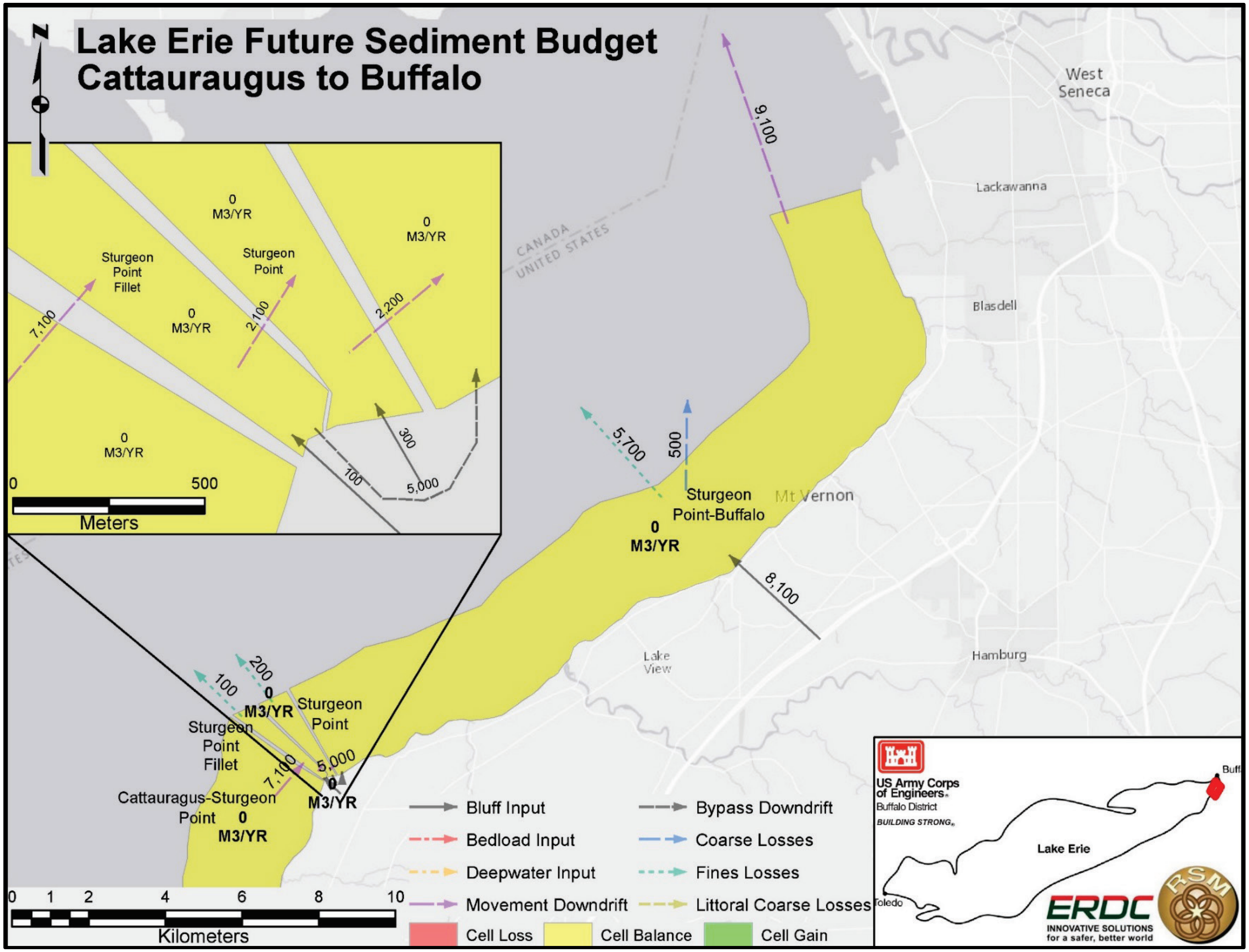


Figure B-60. Cattaraugus to Buffalo Future sediment budget.



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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A sediment budget was developed for the U.S. shoreline of Lake Erie from Maumee Bay, OH, to Buffalo, NY, covering four time frames: (a) Pre-Armoring of the shoreline (1860s–1930s), (b) Mid-Century (mid-twentieth century, 1930s–1970s), (c) Recent era (1970s–2000s), and (d) Future expected conditions (2010+). Sources of data included historic U.S. Army Corps of Engineers Lake Survey charts, aerial photographs, and lidar survey data. The Ohio Department of Natural Resources provided historical recession lines for Ohio. The Pennsylvania Department of Conservation, Natural Resources, and the U.S. Geological Survey supplied historical bluff lines for Pennsylvania.

Analysis of harbor sedimentation and sediment bypassing provides verification of the volume of sediment calculated from bluff recession measurements. These volumes were consistent with harbor sedimentation or sediment bypassing measurements at most points along the shoreline, with the exception of underpredicting sediment volumes at Fairport Harbor, OH.

Most reaches show a decrease in bluff-supplied sediment over time. The decrease is a result of greater bluff armoring during the twentieth century, particularly after the 1970s. For New York and eastern Pennsylvania, the future projected sediment supply from bluffs is similar or slightly less than from the recent era. But in Ohio, the future supply is projected to decrease in most areas because of the almost complete armoring of the Ohio shore.

For the predicted future conditions, total eroded bluff volume will range from 15,000 cubic meters per year in Erie County, NY, to 200,000 cubic meters per year in Ashtabula County, OH.

15. SUBJECT TERMS

Bluff lines, Coast changes, Lake Erie, Regional Sediment Management, Sediment budget, Sediment Budget Analysis System (SBAS), Sediment control, Sediment transport, Shorelines--Monitoring

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